Report of the Hydrogen Production Expert Panel: A Subcommittee of the Hydrogen & Fuel Cell Technical Advisory Committee

*May 2013**

**includes supplemental information added after discussions with the U.S Department of Energy's Hydrogen and Fuel Cell Technologies Program on the original draft submitted in October 2012*

United States Department of Energy
Washington, DC 20585

Acknowledgements

The Steering Committee would like to thank the Department of Energy (DOE) and Hydrogen and Fuel Cell Technical Advisory Committee for supporting the workshop. The time and effort contributed by the expert presenters and workshop participants is also acknowledged. The presentations provided valuable information that enabled the committee to develop findings and make recommendations regarding hydrogen production. Finally, the committee wishes to express its gratitude for the special efforts by several individuals, including Sunita Satyapal (DOE), Eric Miller (DOE), and Melissa Laffen (Alliance Technical Services).

Special thanks to the guest speakers for their insightful comments:

Dr. Steven Chu, Secretary of the United States Department of Energy
Mr. Steven Chalk, Deputy Assistant Secretary for Renewable Energy, U.S. Department of Energy
Dr. Richard Greene, Photochemistry and Biochemistry Team Lead, Office of Basic Energy Sciences, U.S. Department of Energy
Dr. Levi Thompson, Hydrogen Production Expert Panel Chair, Director of the Hydrogen Energy Technology Laboratory and the Richard E. Balzhiser Collegiate Professor of Chemical Engineering at the University of Michigan
Dr. Robert Shaw, Chair, Hydrogen and Fuel Cell Technical Advisory Committee
Dr. Larry Burns, Director of the Roundtable on Sustainable Mobility at The Earth Institute of Columbia University and Professor of Engineering Practice at the University of Michigan
Dr. Mark Cardillo, Executive Director, Camille & Henry Dreyfus Foundation
Dr. Sunita Satyapal, Office Director, Fuel Cell Technologies Office, U.S. Department of Energy

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Abstract

The Steering Committee for the Hydrogen Production Expert Panel was charged with providing recommendations to enable the widespread production of affordable, low carbon hydrogen. The Steering Committee was provided input by experts from industry, academia, and national laboratories via a workshop that was held on May 10-12, 2012. This report summarizes major findings from the workshop and recommendations from the Steering Committee to the Department of Energy. Key recommendations included: 1) providing incentives to accelerate the production of hydrogen for transportation applications with a particular focus on the steam reforming of natural gas, leveraging this abundant and low cost domestic resource; 2) considering significant investments in hydrogen production and storage analyses and demonstrations; 3) developing a cohesive plan for all pertinent research and development programs to provide consistent and long-term guidance; and 4) establishing public-private partnerships and/or clusters to create well-defined plans for infrastructure roll-out, establishing appropriate incentives, and promoting uniform codes, standards, and safety regulations.

Summary of Recommendations to the U.S. Department of Energy

After considering presentations by the expert panel as well as the findings from the working groups, the Steering Committee offers the following overall recommendations to enable the widespread production of affordable, low carbon hydrogen:

- Incentives should be established to accelerate the production of hydrogen from all resources for transportation applications. Given the availability of large and accessible natural gas resources in the United States at historically low prices, hydrogen production using steam methane reforming technology represents an attractive near-term transitional approach.
- Hydrogen is an excellent medium for energy storage and could enable greater penetration of renewables and enhanced grid stabilization. Consequently, the DOE should consider significant investments in both the analysis and demonstration of various hydrogen production and storage technologies.
- The DOE should establish and leverage existing technology working groups to clearly define the specific research advances needed for each technology in order to drive funding strategies and competitive solicitations, similar to the pathway followed for proton exchange membrane (PEM) fuel cells.
- All pertinent offices and programs within the DOE (including Basic Energy Sciences [BES], Energy Efficiency and Renewable Energy [EERE], and Advanced Research Projects Agency-Energy [ARPA-E]), should develop a cohesive plan to provide consistent and longer-term (10-15 years) guidance and support for: 1) interdisciplinary research and development of hydrogen production from renewable resources, 2) detailed analyses of hydrogen production systems, and 3) demonstrations of electrical energy storage from intermittent renewable resources via hydrogen production.
- Communications between EERE, BES, and ARPA-E, as well as other DOE Offices (such as FE and NE) and non-DOE agencies (such as NSF) should be strategically enhanced to foster scientific and technology advances.
- Public-private partnerships and/or clusters should be established to create well-defined plans for infrastructure roll out, establish appropriate incentives, and promote uniform safety regulations, codes, and standards.
- Metrics should be defined to characterize progress of these efforts towards established goals and objectives.
- The government and industry should work together to inform the public and financial communities of the benefits of hydrogen as an energy carrier, thereby dispelling widely held misperceptions regarding near-term commercialization prospects.

Introduction and Overview

With more than 50 million tons produced globally each year, hydrogen is a critical feedstock for the production of clean-burning transportation fuels, fertilizers, and chemicals. Hydrogen also holds great promise as a fuel in high efficiency fuel cells for transportation, back-up power, and grid stabilization applications. Currently, most hydrogen is derived from the steam reforming (SMR) of natural gas; however, hydrogen can also be produced from a variety of renewable resources, including biomass and water. If produced from renewable indigenous feedstocks, the use of hydrogen can significantly reduce our nation's dependence on foreign energy sources and fossil fuels. Hydrogen can also be used to store energy from intermittent renewable sources (e.g., solar and wind). Projected energy storage densities for hydrogen-based systems exceed those of lithium ion batteries, redox flow batteries, and compressed air energy storage.

Since hydrogen for transportation was moved to the forefront of the U.S. energy debate a decade ago, there has been substantial progress towards the use of hydrogen as an energy carrier. For example, the estimated cost of hydrogen fuel cells produced in high-volume has decreased by a factor of six (from $275/kW in 2002 to $49/kW in 2011) and durability in excess of 2,500 hour (or 75,000 miles) has been achieved in vehicle demonstrations. With regard to hydrogen storage, new materials and systems have resulted in an approximately 50% increase in the gravimetric and volumetric capacities since 2007. Progress in the area of hydrogen production has not, however, kept pace with progress in fuel cells and hydrogen storage. This is particularly true for the production of hydrogen from renewable resources.

Within this context, the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) charged the Steering Committee of the Hydrogen Production Expert Panel (HPEP) with providing recommendations to enable the widespread production of affordable, low-carbon hydrogen (see Appendix C). The committee was asked to consider market and business forces (i.e., cost, infrastructure, dispensing, etc.), technology barriers (i.e., scientific, engineering, device-level performance and durability, manufacturing, etc.), and policy barriers, as well as the impact of safety, codes, and standards in formulating recommendations to the Department of Energy (DOE) regarding both policy and investments in research and development for hydrogen production.

Members of the Steering Committee were selected by the HTAC to represent industrial and academic perspectives of hydrogen production. The HPEP Steering Committee consisted of:

- **Dr. Levi Thompson (Chair)**
  University of Michigan
- **Dr. Françoise Barbier**
  Air Liquide
- **Dr. Lawrence Burns**
  University of Michigan & Columbia University
- **Mr. Robert Friedland**
  Proton OnSite
- **Mr. Edward Kiczek**
  Air Products
- **Dr. Arthur Nozik**
  University of Colorado
- **Dr. Geraldine Richmond**
  University of Oregon
- **Dr. Robert Shaw, Jr.**
  Aretê Corporation
- **Mr. Daryl Wilson**
  Hydrogenics

The Steering Committee organized the HPEP workshop with support from the DOE Fuel Cell Technologies Program and Alliance Technical Services. Objectives for the workshop were to:

- Evaluate status and prospects of near- and longer-term hydrogen production technologies
- Identify key technologies and critical challenges
- Prioritize research and development
- Strategize on how to leverage effort among DOE offices

Prior to the formal start of the workshop, key participants, including the Steering Committee and expert presenters, participated in an event during which the Secretary of Energy, The Honorable Dr. Steven Chu, described his view of the strategic importance of hydrogen. Dr. Larry Burns then provided a perspective regarding hydrogen production based on the drivers of transformational change and how hydrogen might create value in the future economy (see Appendix D).

The HPEP workshop took place on May 10-12, 2012 in the Washington, D.C. area. Experts in the field of hydrogen production were invited to give concise presentations describing the current technology status, challenges to near-term implementation, and opportunities for advancements for hydrogen production technologies. Additionally, the experts were asked to make formal recommendations to the Steering Committee. The expert presenters included:

Near-Term Technologies

- **Dr. Katherine Ayers**
  Proton OnSite
- **Mr. Brian Bonner**
  Air Products
- **Mr. Joseph Cargnelli**
  Hydrogenics
- **Mr. Udo Dengel**
  Air Liquide
- **Mr. Pinakin Patel**
  FuelCell Energy
- **Dr. Prabhu Rao**
  Nuvera Fuel Cells

Longer-Term Technologies

- **Dr. Thomas Jarvi**
  Sun Catalytix
- **Dr. Nate Lewis**
  California Institute of Technology
- **Dr. Bruce Logan**
  Pennsylvania State University
- **Dr. John Turner**
  National Renewable Energy Laboratory
- **Dr. Yong Wang**
  Pacific Northwest National Laboratory
- **Dr. Alan Weimer**
  University of Colorado

Biographical sketches of the presenters are provided in Appendix B. Following the presentations, the workshop participants separated into break-out groups where they discussed findings and formulated recommendations for consideration by the Steering Committee. The complete workshop agenda, including break-out group discussion topics, is included in Appendix A.

Key Findings and Recommendations

I. Near-Term Technology Opportunities and Challenges

The expert presenters provided a comprehensive overview of the various hydrogen production technologies now in the market or on the threshold of market entry (see Appendix E for presentation slides). The nominal time window was the next 2-5 years.

The following are the ***key findings*** that emerged from the various break-out group discussions led by Steering Committee members:

- Hydrogen is already a major commodity in the U.S. economy and production could readily be expanded to serve new markets.
  - More than 50 million metric tons are produced annually worldwide (11 million metric tons in the United States), principally from SMR of natural gas. Much of this hydrogen is used in petroleum refineries, in the production of ammonia for fertilizers and other chemicals, and in food processing.
  - Current hydrogen output is sufficient to provide fuel for 250 million fuel cell vehicles worldwide (55 million in the United States).
  - Given the emergence of large and accessible natural gas resources in the United States at historically low prices, hydrogen production using traditional central SMR technology could increase substantially to serve new fuel cell vehicle markets without straining the natural gas supply system and at the same time reduce petroleum imports.

- Large- and small-scale hydrogen production technologies are already commercially available.
  - Central SMR is a mature technology and produces low cost hydrogen in the range of $1.50/kilogram (kg) at plant gate at current (mid-2012) natural gas prices. The cost reduction experience curve indicates a steady but modest 0.5% annual cost decrease over the past 20 years.
  - Hydrogen gas and liquid produced centrally are typically delivered to customer sites by tube trailer or liquid tanker truck. The carriage cost varies with distance traveled but is nominally $1.25/kg.
  - Hydrogen produced in large-scale SMR facilities that is delivered, compressed, and dispensed at a typical station is actually less expensive than gasoline on a miles traveled basis when used in fuel cell electric vehicles (FCEVs). It is likely that a substantial portion of the early hydrogen infrastructure will use this supply mode.
  - Alkaline and proton exchange membrane (PEM) electrolyzers are manufactured by several companies internationally and are currently capable of producing up to 1,000 kg/day with concepts for as much as 50,000 kg/day.

    These products have been available in the market for many years. The cost per kg varies with the electrolyzer size from approximately $6/kg to $15/kg and is heavily dependent on the cost of electricity. At the lower end of this range, the cost of electrolytically produced hydrogen at a typical station is equivalent to gasoline on a miles basis (approximately $3-$5/gallon of gasoline equivalent) if used in a FCEV.
    - Small-scale SMR units are also available commercially and can be economically attractive for industrial applications requiring 1,000 kg/day or greater when the customer site is a significant distance from a central SMR plant. At modest production rates (500 units/year) it is estimated that these units can produce hydrogen at approximately $3-$6/kg.
    - Industrial applications for distributed hydrogen production include food processing, metals, glass, fertilizer production, electric power plant generator cooling, semiconductor manufacturing, analytic laboratory instrumentation, and various meteorological applications.
    - Vehicle fuelling stations (of which there are 60 in the United States and over 200 worldwide) have used all of the technologies mentioned above.

- The principal barrier to cost reduction of distributed hydrogen production systems for vehicle applications is achieving manufacturing scale.
    - Although markets exist for distributed applications, they are relatively small at present and are most attractive for base load and consistent demand requirements. However, the current FCEV fleets are too small and do not meet these demand requirements. For these existing markets, the payback time for investments in product cost reduction is too long to be commercially attractive.
    - Manufacturers generally agree that they face a classic “crossing the chasm” dilemma, even when they can demonstrate cost effectiveness against current fueling options as well as other benefits (e.g. less carbon dioxide on a miles basis).

- Two large-market opportunities could offer the level of manufacturing volume that would allow substantial reductions in the cost of distributed hydrogen production.
    - The FCEV market is the one most discussed and seems to be on the verge of emerging around 2013-2016, particularly in Europe, Japan, and South Korea.
    - The use of hydrogen production as a way to enable renewables by making them dispatchable is a market opportunity of substantial scale that has until recently received less attention than the vehicle opportunity. In this second large application, intermittent (and sometimes stranded) renewable electricity generation is used to produce hydrogen via electrolysis. The hydrogen is stored—for example, in large underground caverns or somewhat smaller above ground tanks—and later used for power generation. Alternatively, the hydrogen produced by renewables could be injected into

gas pipelines for storage as well as transport to load centers (a concept referred to by some manufacturers as "power-to-gas").

- In the very near term, two currently-served markets are providing valuable learning and initial scale.
    - The use of fuel cells in forklifts employed in various industrial and warehouse applications has been an early market for hydrogen. This market could be substantial if all forklifts and similar products (e.g. airport ground equipment) were to switch to fuel cell power. Most customers to date have opted for delivered hydrogen rather than investing in on-site production.
    - Back-up power at remote sites, such as cell towers, has also offered an early market for distributed hydrogen. In virtually all cases to date the required hydrogen has been delivered rather than produced on-site.

Recommendations from the breakout group are clustered into four areas: 1) transportation applications, 2) production and storage applications to enable renewables, 3) education, and 4) research and development (R&D) for cost reduction and performance enhancement.

- Transportation Applications
    - Some form of incentive is required to help encourage owners and operators to proceed with early installation of fueling facilities that may not be economical until the fleet sizes of FCEVs have increased.
    - Suggested incentives include investment tax credits, fuel cost buy-downs, loan guarantees to station owners, fuel tax abatements, operations cost subsidies, and partial grants. Whatever form these incentives take, they need to limit the downside risk that can result from slower than expected demand growth and shorter than anticipated operating times.
    - One novel idea was the suggestion that an agency similar to the Rural Electrification Administration (REA) be created to insure that hydrogen production facilities in remote areas—where natural gas is not available and delivery costs from central facilities are high—be offered economic support in the form of low- or no-cost loans of long duration.
    - Incentives should be designed so that they do not favor any one approach to hydrogen production and should be available to all levels of the supply chain.
    - The cluster approach for early roll-out of hydrogen fueling infrastructure is widely supported. For example, the California Fuel Cell Partnership's latest action plan focuses deployment within five clusters throughout California to support the first large-scale deployment of vehicles in the 2015 time-frame. Research suggests that this strategy can provide adequate coverage and capacity for early markets and improves the business case for station operators.
    - A public-private partnership (preferably on an equity basis) with all critical stakeholders should be considered to create a concrete plan for

infrastructure roll-out, establish appropriate incentives, and promote uniform safety regulations, codes, and standards.

- Hydrogen Production and Storage to Enable Renewables
  - The principal applications in this area being pursued in North America and Europe are focused on addressing the intermittency of solar and wind power generation using electrolysis technologies. There is also ongoing work in biomass reforming and related approaches to hydrogen production. It is recommended that:
    - Detailed system studies should be conducted with utility partners to understand the dynamics of the interaction of the grid with large-scale renewable generation accompanied by hydrogen production and storage.
    - At least two demonstrations at modest scale (at least 10 megawatts) should be funded, one with solar and the other with wind, to analyze with hard data the performance and ancillary benefits of various storage systems. These demonstrations should be cost-shared with industry.
  - Programs should also be established to gather real world data on:
    - The economic value of injecting renewably-generated hydrogen into the natural gas pipeline system as a storage and energy transportation approach.
    - The economics and performance of alternative separation technologies to extract hydrogen from the natural gas stream at sufficient purity for various applications.
  - Continued effort should be devoted to establishing the economic value and improving the performance and reliability of tri-generation systems producing power, heat, and hydrogen from biogas and waste streams.

- Education
  - The panel felt that substantially enhanced efforts by government and industry to inform the public on the benefits of producing hydrogen as an energy carrier, whether from natural gas or renewables, should be initiated with the highest sense of urgency.
    - There is a widely held public perception that hydrogen is an energy option for the distant future and that there are unresolved safety issues.
    - The panel has demonstrated conclusively that there are plentiful technology options available in the market now and that the safety track record is excellent.
  - There is an equally important need to work with codes and standards officials, as well as fire marshals and other public safety officials, to ensure that commercialization barriers resulting from lack of knowledge are removed.
  - The sense in the financial community is that for the past several years, hydrogen and fuel cell technology has not been accepted as an energy option

    by the DOE. As a far more supportive perspective is emerging due to the types of success in the near term described above, it is important to send a favorable signal widely and publicly.
  - Finally, it would be desirable to develop a consensus among government and industry participants on a pathway for the roll-out of a hydrogen supply infrastructure concurrent with the introduction of FCEVs and then publicize the economic, environmental, and security benefits of implementing this plan.

- Research and Development
  - While the corporate participants in the hydrogen production arena undertake continuous efforts to improve the performance and cost effectiveness of their products, there are some areas of R&D that cut across all participants where government support would be helpful.
  - With regard to PEM electrolyzers, there is need for improved materials to address membrane permeation, strength, and ductility issues, especially at elevated temperatures. Research to develop entirely new membrane technology that is much lower cost and can tolerate higher temperatures and pressures than membranes currently used is also recommended. Additionally, there is need for an improved basic understanding of coating technologies to enable less expensive cell components without sacrificing durability. To the maximum extent possible the major advancements in the fuel cell area, particularly in catalyst composition and loading, membrane performance, and cell stack hardware, should be leveraged for use in PEM electrolysis.
  - The main areas for future cost reduction in all the approaches for distributed hydrogen production have to do with balance of plant, including:
    - Reduction of the energy used for “hotel load” – pumps, controls, etc.
    - Efficient and cost effective power electronics
    - Drying of the hydrogen stream produced by electrolysis and optimization of electrochemical vs. mechanical compression
    - Gas clean-up technologies (e.g. pressure swing absorption units) for use in SMRs
    - System adaptation to variable demand
    - Storage systems
  - As noted earlier, there is need for R&D on gas separation technologies to extract pure hydrogen (perhaps up to 99.999%) from natural gas pipelines having hydrogen concentrations up to 5%, and from gas streams having hazardous components.

II. Longer-Term Technology Opportunities and Challenges

While there are "longer-term" opportunities for efficiency and cost advancements in technologies that are commercial today, discussion of those opportunities was included in the previous section of this report. For the purposes of this section, "longer-term" technologies are defined as those that may have shown feasibility at a lab-scale but are at least five years from commercialization at any scale. Presentations were given at the workshop on a number of early-stage hydrogen production R&D activities, including advanced bioelectrochemical, solar thermal, photoelectrochemical, microbial, and biomass production techniques. These presentations were not intended to be all-inclusive, but illustrate the type of research efforts being supported by the DOE Basic Energy Sciences Program (BES), the DOE Advanced Research Projects Agency-Energy (ARPA-E), the National Science Foundation, and other agencies. The key findings reported in this section are not intended to duplicate what has been described in other reports such as "Basic Research Needs for the Hydrogen Economy," the report from the Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use held May 13-15, 2003.

The following ***key findings*** emerged from the various breakout group discussions focused on longer-term issues:

- The time required to take a hydrogen production technology from the R&D stage to the commercial market is very long (often 20-30 years) and the cost of completing the full development cycle can be very high.
    - To develop to the point where they can be considered by investors and industry, longer-term technologies typically require a long-term commitment with a consistent funding base.
    - Even when proof of principle has been demonstrated, it can take 10-15 years to convert bench-scale results, or even early prototype products, into a commercial product that is cost effective and has demonstrated performance over commercially acceptable time periods.
    - In some cases, concepts that appear interesting at the lab-scale cannot be developed into products that are competitive commercially.
    - The resources required to make the transition from R&D to commercial product can often be in excess of $100 million for a single technology.

- The objective of DOE's hydrogen production R&D program should be to explore as many novel concepts as possible at the early stage.
    - This strategy could eliminate work on approaches that do not seem to have a reasonable chance of commercial success.
    - Provide funding opportunities for new R&D efforts as fresh ideas are generated.

- Successful commercial R&D-oriented institutions (e.g., Bell Labs, GE Research) have developed effective management approaches that link basic and applied research with commercial product development. Efforts at DOE to emulate these approaches should be maintained and strengthened.
    - There is a good portfolio of basic research projects sponsored by DOE (e.g., at BES and BER), many of which are being carried out by university teams. The processes that DOE uses for selecting these projects and developing research plans appears to be working well.
    - While efforts within DOE's basic research programs have not been specifically targeted at hydrogen production, some have been of direct scientific relevance. It is important to support formal mechanisms that allow effective communications between the applied hydrogen production programs (e.g., EERE Fuel Cell Technologies) and these basic programs to ensure that the R&D needs of both near- and longer-term hydrogen production approaches are being addressed.
    - Communications between EERE, BES, and ARPA-E, as well as other DOE Offices (such as FE and NE) and non-DOE agencies (such as NSF) should be strategically enhanced to accelerate scientific and technological advances.

Assessing the promise and capabilities of these advanced concepts was not a straight-forward task. However, in the context of providing industry with innovative concepts that are relevant to their markets, the following ***recommendations*** are offered:

- DOE is encouraged to strengthen cross-cutting teams, emulating for example networking/linking pin teams (*The Tipping Point*, by Malcolm Gladwell [2000]), to promote effective communication and scientific exchange between the basic and applied programs.
    - Members of such teams should be excellent communicators and should have sufficient technical and personal skills, and experience to interact effectively with each other and with the R&D community.
    - Regular meetings and workshops led by this networking team should be encouraged to discuss successes and explore ways to make the interaction process ever more successful.
    - Team activities and performance should be evaluated jointly by all groups with whom they interact on a regular basis with a goal of continued process improvements and refinements.

- Cross-cutting research can shorten the timeline for discovery and problem solving. DOE should continue existing initiatives and support new initiatives for assembling diverse groups of disciplines to attack specific technical roadblocks to the different renewable hydrogen production pathways

  - Interdisciplinary scientific teams (biologists, computer scientists, physicists, chemists, and engineers) can often be a powerful tool to solve complex problems related to renewable hydrogen production.
    - As an example, the development of more efficient solar absorber materials for photoelectrochemical hydrogen production (as well as for photovoltaics) could be facilitated by the integration of computational science with state-of-the-art materials discovery and with experimental synthesis and characterization techniques.
    - As a further example, solar-energy based water-splitting systems will produce hydrogen over large areas, creating challenges for water management and gas collection. This represents a significant engineering challenge that should be addressed early by the scientists and engineers alike.

- Basic science research is an important part of the overall DOE portfolio, but stronger links between scientific discovery and potential applications are needed in order to leverage advancements in fundamental and applied research that could assist both near- and longer-term technologies.
  - DOE should continue developing stronger links to industry to help in identifying R&D initiatives that industry experts feel have commercial promise.
  - Refinement of hydrogen production pathways/roadmaps that further integrate near-term with longer-term pathways rather than separating them would encourage the bridging of technologies across applications.

- In all fundamental and applied R&D initiatives, clear and meaningful metrics are critical for gauging programmatic success and for measuring progress toward clearly established goals.
  - DOE should continue to evaluate, refine and strengthen its metrics-based assessment approaches for managing all projects including those at universities and national laboratories as well as the large collaborative initiatives such as the Energy Frontier Research Centers and the Energy Innovation Hubs.
  - R&D for hydrogen production technologies should include programmatic goals and metrics that include scalability of the technology to facilitate large-scale and distributed production.
  - Specific quantitative metrics are essential to drive technology advances in the near-term hydrogen production pathways. While metrics may not be as quantitative for the longer-term hydrogen production pathways, a cohesive set of meaningful scientific metrics needs to be defined and refined through consensus among the fundamental and applied researchers. This is important to the overall vision of the hydrogen production programs at DOE, allowing for the assessment of forward progress in a consensus framework.

- As the applied R&D and technology validation programs for hydrogen production proceed they should be required to prepare high-fidelity estimates of anticipated product costs and physical sizes per unit output so that assessments of relative merit can be conducted.
    - Technoeconomic analysis can be a powerful tool in identifying research areas with the maximum impact on the final product costs, and DOE should be encouraged to strengthen its core capabilities in technoeconomic analysis of all energy technologies.
        - As one example, technoeconomic analysis of photoelectrochemical hydrogen production showed that the solar-to-hydrogen conversion efficiency had the largest impact on hydrogen production costs (greater, for example, than panel costs and system durability); in turn facilitating the establishment of meaningful metrics and targets for cost-effective hydrogen production.

- Meeting the hydrogen supply needs requires an accurate and realistic understanding of the available biomass feedstock resource. This is critical knowledge which will enable DOE to effectively plan its biomass-to-hydrogen production scenarios.
    - Biomass waste streams from bio-refineries and municipal solid waste represent a near-term, low-cost feedstock for hydrogen production, but they are poorly characterized as to organic species, impurities, and their potential for hydrogen production from these waste streams.
    - A realistic assessment of the hydrogen production efficiencies and loss mechanisms for these varied waste streams can help in maximizing the value of these resources.

- DOE should continue/expand R&D funding of different renewable hydrogen production technologies which leverage the scientific focus areas currently being funded by the fundamental research programs. For example:
    - Explore the hydrogen production potential of advances in genomics and in synthetic biology.
    - Expand exploration of photoelectrochemical water splitting technologies that are based on two optimized semiconductor photoelectrodes, including the use of buried photovoltaic junctions
    - Expand exploration of advanced electrolyzer technologies, such as anion-exchange-membranes (AEM) to reduce materials cost and high-temperature electrolysis to reduce cost through efficiency enhancements.
    - Explore synergies between high-temperature solar-fuels processes and thermochemical cycles for solar/nuclear hydrogen production.

- Policies that encourage longer-term R&D should be considered.
    - Hydrogen production could be used as an example to re-establish the importance of science and technology in the public eye.
    - Assure that the nation maintains a leadership position not only in energy research, but in all fields.

Appendix A

Hydrogen Production Expert Panel Workshop Agenda

Hydrogen & Fuel Cell Technical Advisory Committee: Hydrogen Production Expert Panel Subcommittee

Marriott Crystal Gateway, 1700 Jefferson Davis Highway, Arlington, VA 22202

May 10th – 12th, 2012

Panel Objectives

- **Provide recommendations to the Hydrogen & Fuel Cell Technical Advisory Committee (HTAC) to enable a path forward for the widespread production of affordable low carbon hydrogen.**
  - ***Evaluate current status of hydrogen production technologies***
  - ***Identify remaining challenges***
  - ***Prioritize R&D needs***
  - ***Strategize how to best leverage R&D among U.S. Department of Energy Offices and with other agencies***

THURSDAY EVENING, MAY 10TH KICK-OFF

Kick-Off Session: Vision and Goals

Location: Salon H

6:00–6:10 PM **HTAC Chair Welcome**
- Dr. Robert Shaw, Chair, Hydrogen & Fuel Cell Technical Advisory Committee (HTAC)

6:10–6:20 PM **U.S. Department of Energy Welcome**
- The Honorable Dr. Steven Chu, Secretary, U.S. Department of Energy

6:20–6:35 PM **A Vision for Hydrogen's Role in the Energy Portfolio**
- Dr. Larry Burns, Director of the Roundtable on Sustainable Mobility, The Earth Institute, Columbia University

6:35–6:45 PM **Panel Overview and Workshop Agenda**
- Dr. Levi Thompson, Panel Chair and Director, Hydrogen Energy Technology Laboratory, University of Michigan

7:00–8:30 PM **Follow-on Discussion / Working Dinner**

8:30–8:45 PM **Steering Committee Briefing Session**

Friday, May 11th Workshop

Session 1: Near-Term Technology Opportunities and Challenges

Location: Salons J & K

8:00–8:30 AM **Meet and Greet over Coffee**

8:30–8:45 AM **U.S. Department of Energy Welcome: Importance of Panel Workshop**

Mr. Steven Chalk, Deputy Assistant Secretary for Renewable Energy, U.S. Department of Energy

8:45–9:00 AM **Success Stories and Near-Term Opportunities**

Dr. Larry Burns, The Earth Institute, Columbia University

9:00–9:10 AM **Panel Welcome and Steering Committee Introductions**

Dr. Levi Thompson, Panel Chair and Director, Hydrogen Energy Technology Laboratory, University of Michigan

Steering Committee:

- *Dr. Françoise Barbier, Air Liquide*
- *Dr. Lawrence Burns, The Earth Institute, Columbia University*
- *Robert Friedland, Proton Onsite*
- *Edward Kiczek, Air Products*
- *Dr. Arthur Nozik, University of Colorado*
- *Dr. Geraldine Richmond, University of Oregon*
- *Dr. Robert Shaw, Aretê Corporation*
- *Daryl Wilson, Hydrogenics*

9:10–10:40 AM **Near-Term Technology Opportunities & Challenges Technical Expert Presentations:**

- *Udo Dengel, Air Liquide*
- *Brian Bonner, Air Products*
- *Dr. Prabhu Rao, Nuvera Fuel Cells*
- *Pinakin Patel, FuelCell Energy*
- *Dr. Katherine Ayers, Proton Onsite*
- *Joseph Cargnelli, Hydrogenics*

10:40–10:50 AM **Break**

10:50–12:20 PM **Break-Out Sessions** **topics subject to change by panel.**

Locations: Jefferson, Lee, Salon D, and Salon E

A. *Scientific/Engineering Challenges*
B. *Commercialization Challenges; Cost Reductions Needs & Strategies*
C. *Competitive Landscape; Impact of Natural Gas on Hydrogen Market*
D. *Bridging from Fossil-based Reforming to Renewable Production*

12:20–1:30 PM **Working Lunch: Report-out and Discussion**

Locations: Salons J & K

FRIDAY, MAY 11TH WORKSHOP

Session 2: Longer-Term Technology Opportunities and Challenges

Location: Salons J & K

1:30–1:45 PM **Scientific Challenges and Innovative Approaches in Renewable Energy and Hydrogen Research**

Dr. Richard Greene, Photochemistry and Biochemistry Team Lead, Office of Basic Energy Sciences, U.S. Department of Energy

1:45–2:00 PM **Examples of Lab to Markets- New Advances & Technological Opportunities**

Dr. Mark Cardillo, Executive Director, Camille & Henry Dreyfus Foundation

2:00–3:30 PM **Longer-Term Technology Opportunities & Challenges**
Technical Expert Presentations:

- *Dr. John Turner, National Renewable Energy Laboratory*
- *Dr. Thomas Jarvi, Sun Catalytix*
- *Dr. Bruce Logan, Pennsylvania State University*
- *Dr. Alan Weimer, University of Colorado*
- *Dr. Yong Wang, Pacific Northwest National Laboratory*
- *Dr. Nathan Lewis, California Institute of Technology*

3:30–3:45 PM **Break**

3:45–5:15 PM **Break-Out Sessions** **topics subject to change by panel**

Locations: Jefferson, Lee, Salon D, and Salon E

E. Scientific/Engineering Challenges to Renewable Integration
F. Direct Renewable Production Using Photolytic and Thermolytic Processes
G. Bio-resources, including Biomass, Biogas, and Biological Processes
H. Best Leveraging of Latest Scientific Developments

5:15–6:15 PM **Report-out and Discussion**

Location: Salons J & K

6:15–7:00 PM **Break / Ad Hoc Break-Outs**

7:00–8:30 PM **Working Dinner and Discussion for Steering Committee and Expert Panelists**

Location: Salons H

Saturday, May 12th Report Session

Session 3: Panel Findings and Recommendations

Location: Salons J & K

8:30–8:45 AM

Hydrogen and Fuel Cells Program at the U.S. Department of Energy

- Dr. Sunita Satyapal, Program Manager, Fuel Cell Technologies Program, U.S. Department of Energy

8:45–10:15am

Major Findings from Near-Term Technology Session

Dr. Robert Shaw, coordinator:

- Reforming Technologies: Status, Challenges, Opportunities, and Recommendations
- Electrolytic Technologies: Status, Challenges, Opportunities, and Recommendations
- Identifying Synergies and Cross-cutting Issues
- Key Recommendations to U.S. Department of Energy
- Next Steps

10:15–10:30 AM

Break

10:30–11:45 AM

Major Findings from Longer-Term Technology Session

Dr. Levi Thompson, coordinator:

- Renewable Water-splitting Pathways (including Advanced Electrolysis, Photolysis, Thermolysis): Status, Challenges, Opportunities, and Recommendations
- Bio-resource Pathways (including Biomass, Biogas, and Biological processes): Status, challenges, opportunities and recommendations
- Identifying Synergies and Cross-cutting Issues
- Key recommendations to U.S. Department of Energy
- Next Steps

Session 6: Prepare Report Draft (Working Lunch)

Location: Salons J & K

11:45–2:45 PM

- Refine and Integrate Recommendations
- Outline Report
- Prepare Initial Draft
- Make Final Writing Assignments
- Adjourn

Appendix B

Biographies of Hydrogen Production Expert Panelists

BIOGRAPHIES

Hydrogen Production Expert Panel:

A Subcommittee of the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)

Dr. Katherine Ayers, Director of Research, Proton OnSite

Dr. Ayers is the Director of Research at Proton OnSite, a company specializing in the design and manufacture of PEM electrochemical systems for hydrogen production, with over 8MW installed in more than 70 countries, exceeding 1,800 fielded systems. She is responsible for developing the long-term research direction for improvements in performance, reliability, and cost of Proton's electrolyzer cell stack as well as overseeing Proton's military and aerospace programs. Prior to joining Proton Energy Systems, Dr. Ayers served as a Staff Electrochemist and project team leader at Energizer Battery Company. She has served as Principal Investigator on multiple contract research projects from the U.S. DOE, Office of Naval Research, and National Science Foundation, and was recently awarded an ARPA-E grant to develop a novel, low cost regenerative fuel cell system. Dr. Ayers earned her Ph.D. in Electrochemistry from the California Institute of Technology and is the author of several peer-reviewed journal publications and two U.S. patents.

Dr. Françoise Barbier, Program Director, Hydrogen Energy Research and Development, Air Liquide

Dr. Barbier is the Program Director of the Hydrogen Energy Research and Development program at Air Liquide, where she also serves as the International Senior Expert in the field of energy. She is responsible for technology development in areas including renewable hydrogen production, storage, distribution, fuel cells, materials compatibility and safety. Dr. Barbier earned her doctorate degree in Materials Science from the University of Orsay - Paris Sud, and started her career as a researcher at the National Center of Scientific Research in France. Starting in 1992, she worked at the French Atomic Energy Commission, offering expertise in materials for nuclear reactors and in hydrogen and fuel cells. Since joining Air Liquide in 2007, her responsibilities have also included the coordination of the French Fuel Cell Research Network (PACo) set up by the Ministry of Research. Dr. Barbier is the co-author of more than 100 scientific publications.

Brian Bonner, Global Product Manager, Hydrogen Energy Systems, Air Products

As Global Product Manager of Hydrogen Energy Systems, Mr. Bonner leads the development of Air Products' hydrogen supply chain strategies to support product development, market positioning, and introduction of hydrogen-based fueling systems for the emerging hydrogen and alternative energy economy. Air Products is a leading world supplier of merchant hydrogen from more than 60 production sites, and delivers hydrogen through over 700 miles of pipeline and via one of the world's largest liquid and gas tank truck fleets. They have experience providing hydrogen at more than 140 hydrogen fueling stations in 19 countries around the world and are approaching 1 million hydrogen vehicle refuelings. Mr. Bonner also works with industry stakeholders in assessing new technology, economics, and environmental legislation for the early-stage, transitional, and long-term hydrogen economy. He holds a degree in Operations Research and Management Science from Penn State University and has post-graduate development and training at the Institute for the Study of Business Markets at Penn State and the Metals Engineering Institute. Mr. Bonner has authored and published a number of technical papers and has 16 U.S. and international patents.

Dr. Lawrence Burns, Director, Program on Sustainable Mobility, The Earth Institute, Columbia University

Dr. Burns currently serves as the Director of the Program on Sustainable Mobility with The Earth Institute at Columbia University. Additionally, he is a Professor of Engineering Practice at the University of Michigan, and serves as Senior Advisor to the Chairman of Hess Corporation, a consultant to Google Inc., Vice Chairman of the Midwest Research Institute, a member of the CleanTech Advisory Council with Vantage Point Capital Partners, and an Advisory Council Member of Greentech Capital Advisors Securities, LLC. Dr. Burns completed a distinguished career with General Motors, after serving as Corporate Vice President of R&D and Strategic Planning from 1998-2009. In this role, he oversaw GM’s advanced technology and innovation programs for all of GM’s powertrain platforms and reported directly to its CEO/President. In addition, he led GM’s development of new automotive “DNA” that married electrically driven and “connected vehicle” technologies in pursuit of affordable, sustainable, and personal smart vehicles. From 1988-1997, he held a wide range of leadership positions at GM, including industrial engineering, quality, production control, product/manufacturing/business planning, and product program management. Dr. Burns holds a Ph.D. in Civil Engineering from the University of California at Berkeley, where he is a member for the Advisory Council for its Institute of Transportation Studies. He earned his master’s degree in engineering and public policy from the University of Michigan and his bachelor’s degree in mechanical engineering from General Motors Institute (now Kettering University). He was elected into the National Academy of Engineering in 2011.

Joseph Cargnelli, Co-Founder and Chief Technology Officer, Hydrogenics

In addition to Mr. Cargnelli’s role as CTO for Hydrogenics, he has also served as the Vice President of Technology since 1995. Hydrogenics is a Canadian company with over 60 years of experience designing, manufacturing, building, and installing industrial and commercial hydrogen systems around the world, with over 1,800 units installed in over 100 countries. Mr. Cargnelli is also the Director of Stuart Energy, a Hydrogenics subsidiary. In 2002 Mr. Cargnelli was selected as one of the world’s top 100 young innovators by *Technology Review*, MIT’s magazine of innovation. He previously worked as a Research Engineer with the Laboratory of Advanced Concepts in Energy Conversion Inc., a laboratory engaged in the research, development, and demonstration of alkaline fuel cells and hydrogen storage methods. His professional affiliations include the Professional Engineers of Ontario, Canada. Mr. Cargnelli holds an M.S. and B.S. in Mechanical Engineering from the University of Toronto.

Udo Dengel, Sales Manager of Onsite Hydrogen, Air Liquide

Mr. Dengel is Sales Manager of Onsite Hydrogen at Air Liquide’s HYOS team in Washington DC. Air Liquide produces over seven billion cubic meters of hydrogen annually, with revenues exceeding 1,200 million euros per year. In his current capacity, Mr. Dengel is responsible for business development and the sale of onsite hydrogen plants based on technology acquired by Air Liquide from H2Gen Innovations. Before joining Air Liquide, he was the International Sales Director at H2Gen where he successfully launched their onsite hydrogen generation and gas purification technologies in international markets. Prior to his work in the hydrogen technology sector, Mr. Dengel worked as Controller and Key Account Manager at MTS GmbH in Munich, Commercial Director at Southside Thermal Sciences Ltd. in London, and Project Manager at ZF Friedrichshafen AG. He holds an M.B.A. and a B.S. in Industrial Engineering, and attended the Imperial College London, the Fachhochschule Esslingen - Hochschule für Technik, and the Université de Technologie de Compiègne, France.

Robert Friedland, Co-Founder, President, and Chief Executive Officer, Proton OnSite
Proton OnSite was founded in 1996 and specializes in the design and manufacture of proton exchange membrane (PEM) electrochemical systems for hydrogen production, with over 8MW installed in more than 70 countries, exceeding 1,800 fielded systems. Before being appointed President and CEO, Mr. Friedland held various positions of increasing responsibility at Proton including Chief Operating Officer and Senior Vice President of Products and Manufacturing. Mr. Friedland is an internationally-recognized expert in the hydrogen energy and fuel cell industry, and has over 23 years of experience that span engineering, manufacturing, finance and operations. Prior to 1996, Mr. Friedland spent nine years at Hamilton Sundstrand, a division of United Technologies, where he was the Program Operations Manager of Navy and Electrochemical Systems. He has delivered numerous papers and presentations on current and future uses of hydrogen. Mr. Friedland earned his B.S. in Mechanical Engineering from Syracuse University and his M.B.A. from Rennselaer Polytechnic Institute.

Dr. Thomas Jarvi, Chief Technology Officer, Sun Catalytix
Sun Catalytix is an energy storage and renewable fuels technology company founded to commercialize groundbreaking science from the research laboratory of Professor Daniel Nocera at MIT. Prior to joining Sun Catalytix as the Chief Technology Officer in 2010, Dr. Jarvi was the Director of Cell Stack Engineering at UTC Power Corporation, a United Technologies Company that has established itself as a world leader in fuel cell technology and deployment. He also served as Director of Technology Development for UTC Power, with responsibility for overall technology planning and program execution. Dr. Jarvi started his industrial career at United Technologies Research Center in 1998, where he focused on research into fundamental degradation mechanisms of fuel cells. He has published over a dozen papers in electrochemistry and fuel cells, and is co-inventor on ten issued or pending patents. He received his Ph.D. from the University of Washington in 1998 and his B.S. from the University of Illinois in 1993, both in Chemical Engineering.

Edward Kiczek, Global Business Director, Hydrogen Energy Systems, Air Products
Mr. Kiczek has been employed with Air Products for 25 years and currently serves as the Global Business Director for Hydrogen Energy Systems. Air Products is a leading world supplier of merchant hydrogen from more than 60 production sites, and delivers hydrogen through over 700 miles of pipeline and via one of the world’s largest liquid and gas tank truck fleets. They have experience providing hydrogen at more than 140 hydrogen fueling stations in 19 countries around the world and are approaching 1 million hydrogen vehicle refuelings. Mr. Kiczek’s responsibilities include strategic alliances, joint ventures, and equity investment opportunities related to alternative fuels and complementary offerings to Air Products’ core hydrogen business to position the company to serve evolving alternative energy markets, including personal vehicles, fleet vehicles, stationary power and auxiliary power applications. His efforts include worldwide legislative positioning of the groups’ efforts to obtain federal support. Mr. Kiczek has participated on the Boards of several start-up companies and sits on the Board of the Center for Transportation Excellence. Under Mr. Kiczek’s leadership the group’s commercial revenues have doubled over the last 3 years in which he has taken the group to profitability. Mr. Kiczek has been awarded 18 patents in various areas, and has an M.S. in Mechanical Engineering from Stevens Institute of Technology and an M.B.A. from Fairleigh Dickinson University.

Dr. Nathan Lewis, George L. Argyros Professor of Chemistry, California Institute of Technology
Dr. Lewis has been on the faculty at the California Institute of Technology since 1988 and is the George L. Argyros Professor of Chemistry. He specializes in functionalization of silicon and other semiconductor surfaces, as well as chemical sensing using chemiresistive sensor arrays. Dr. Lewis has served as the Principal Investigator of the Beckman Institute Molecular Materials Resource Center at Caltech since 1992, and is the director of the Joint Center for Artificial Photosynthesis, DOE's Energy Innovation Hub on Fuels from Sunlight. He was on the faculty of Stanford from 1981 to 1986, as an assistant professor and as a tenured Associate Professor. Dr. Lewis has been an Alfred P. Sloan Fellow, a Camille and Henry Dreyfus Teacher-Scholar, and a Presidential Young Investigator. He received the Fresenius Award in 1990, the ACS Award in Pure Chemistry in 1991, the Orton Memorial Lecture award in 2003, the Princeton Environmental Award in 2003 and the Michael Faraday Medal of the Royal Society of Electrochemistry in 2008. He has published over 300 papers and has supervised approximately 60 graduate students and postdoctoral associates. Dr. Lewis was named the 17th greatest effector of change by *Rolling Stone* magazine, and has been appointed chair of the Editorial Board for the Royal Society of Science journal *Energy and Environmental Science*. He obtained his B.S. and M.S. degrees at Caltech under Harry B. Gray in 1977 studying the redox reactions of inorganic rhodium complexes. He received a Ph.D. from the Massachusetts Institute of Technology in 1981 for his work under Mark S. Wrighton studying semiconductor electrochemistry.

Dr. Bruce Logan, Kappe Professor of Environmental Engineering, Pennsylvania State University
In addition to being an endowed Professor of Environmental Engineering at Penn State University, Dr. Logan serves as Director of both Penn State's Hydrogen Energy Center and College of Engineering Environmental Institute. He has published over 200 journal articles and numerous books in research areas that include bioenergy production, bioremediation, environmental transport processes, colloidal dynamics, and microbial adhesion. Dr. Logan is a visiting professor at Newcastle University in England and Harbin Institute of Technology in China, and an investigator with the King Abdullah University of Science and Technology in Saudi Arabia. Prior to joining the faculty at Penn State in 1997, he was on the faculty at the University of Arizona in the Department of Chemical and Environmental Engineering. He received his M.S. in Environmental Engineering from Rensselaer Polytechnic Institute and his Ph.D. in Environmental Engineering from the University of California, Berkeley.

Dr. Arthur Nozik, Senior Research Fellow Emeritus, National Renewable Energy Laboratory
Dr. Nozik is a Senior Research Fellow Emeritus at the U.S. DOE National Renewable Energy Laboratory (NREL) and Professor Adjoint in the Chemistry Department at the University of Colorado, Boulder. Before joining NREL in 1978, he conducted research at the Allied Chemical Corporation and American Cyanamid Corporation. Dr. Nozik's research interests include size quantization effects in semiconductor quantum dots and quantum wells (and the applications of these nanostructures to solar photon conversion), photogenerated carrier relaxation dynamics in semiconductor structures, photoelectrochemistry of semiconductor-molecule interfaces, photoelectrochemical energy conversion, and photocatalysis. He holds 11 U.S. patents and has published over 250 papers and book chapters in these fields. He has served on numerous scientific review and advisory panels and received several awards in solar energy research. Dr. Nozik has been a Senior Editor of *The Journal of Physical Chemistry* since 1993, and serves on the Editorial Boards of the journals *Energy and Environmental Science*, *Solar Energy Materials and Solar Cells*, and *NanoEnergy*. He is also a Fellow of the American

Physical Society and the American Association for the Advancement of Science. He received his BChE from Cornell University in 1959 and his Ph.D. in Physical Chemistry from Yale University in 1967.

Pinakin Patel, Director of Special Systems and Research, FuelCell Energy
As the Director of Special Systems and Research at FuelCell Energy, Mr. Patel is responsible for development of innovative fuel cell applications using high temperature fuel cells including carbonate, solid oxide and PEM. He is responsible for the research and development of low-cost solutions for hydrogen infrastructure for fuel cell vehicles, particularly using renewable fuels such as ethanol, bio-diesel, glycerol, and waste-derived biogas. Mr. Patel has led collaborative research, development and demonstration efforts with international companies, such as Sanyo and Mitsubishi in Japan, Haldor Topsoe and Elkraft Power Co. in Denmark, Daimler-Chrysler (MTU division) in Germany, and Hydrogen companies such as Air Products, Linde-BOC, and Air Liquide. He has authored or co-authored over 100 publications and seminar presentations, and holds 15 patents. Mr. Patel holds an M.S. in Chemistry from Illinois Institute of Technology, and a B.S. in Chemical Engineering from M.S. University of Baroda, India.

Dr. Prabhu Rao, Vice President of Commercial Operations, Nuvera Fuel Cells
Nuvera Fuel Cells is a leading company in the development and advancement of multi-fuel processing and fuel cell technology, including natural gas reformers. In his current position as Vice President of Commercial Operations, Dr. Rao oversees the company's distributed generation and hydrogen production product lines. He has been instrumental in the successful implementation of the ISO quality system at Nuvera. Dr. Rao has also served as Nuvera's Vice President of Product Development and Manufacturing activities, where he facilitated the development of the company's stationary and industrial products. Previously, he was a Co-Founder of Epyx Inc. which later merged with DeNora Fuel Cells to become Nuvera. At Epyx, he led the automotive business team and launched successful joint development activities with companies such as Renault and Peugeot. Dr. Rao is currently the Co-Chair of The Indus Entrepreneurs' CleanTech & Energy SIG. He holds a Ph.D. in Mechanical Engineering and an M.S. in Mechanical Engineering and Environmental Engineering from Drexel University, and earned his B.S. in Mechanical Engineering from the Indian Institute of Technology, Madras.

Dr. Geraldine Richmond, Richard M. and Patricia H. Noyes Professor, Department of Chemistry, University of Oregon
Dr. Richmond is the Richard M. and Patricia H. Noyes Professor in the Department of Chemistry at the University of Oregon. She has distinguished herself in research using nonlinear optical spectroscopy and computational methods applied to understanding the chemistry that occurs at complex surfaces and interfaces that have relevance to important problems in energy production, environmental remediation, atmospheric chemistry and biomolecular surfaces. Over 160 publications have resulted from this research. Dr. Richmond has also played an important role in setting the national scientific agenda through her service on many science boards and advisory panels. Most recent appointments include Associate Editor of Annual Reviews of Physical Chemistry (2006-2008), Chair of the Science Advisory Committee of the Stanford Synchrotron Radiation Laboratory (2006-2008), and Chair of the Chemistry Section, Association for the Advancement of Science (AAAS) (2009-2010). She is the founder and chair of the Committee on the Advancement of Women Chemists, an organization assisting in the advancement of women faculty in the sciences, for which she was awarded the Presidential Award for Excellence in Science and Engineering Mentoring (1997). Dr. Richmond received her Ph.D. in

Chemical Physics at the University of California, Berkeley, where she worked under the mentorship of Prof. George Pimentel.

Dr. Robert W. Shaw, Jr., President and founder, Aretê Corporation
Dr. Shaw is President and founder of Aretê Corporation, a venture capital firm focused on alternative energy technologies. He founded Aretê in 1983 and led the Utech and Micro-Generation Technology Fund investment teams. Prior to forming Aretê, Dr. Shaw was Senior Vice President of Booz, Allen & Hamilton's Energy Division and a member of the firm's Board of Directors. He has served as Chairman and Director of Evergreen Solar, Inc. (ESLR), Distributed Energy Systems Corporation (DESC), CTP Hydrogen Corporation, and Superconductivity, Inc. (sold to American Superconductor Corporation, AMSC) and as a Director of H2Gen Innovations, Inc. He has also held advisory positions on numerous venture and private equity firms. Earlier in his career, Dr. Shaw conducted materials and electronics research at Bell Laboratories and the Cavendish Laboratory in the U.K. He holds a Ph.D. in Applied Physics from Stanford University, an M.P.A. in Organization Design and Development from American University, and an M.S. in Electrical Engineering and a B.E.P. from Cornell University. Dr. Shaw is also a member of the Cornell University Engineering College Council and a trustee of the Society for Science and the Public.

Dr. Levi Thompson, Director, Hydrogen Energy Technology Laboratory, University of Michigan
Dr. Thompson is the Richard E. Balzhiser Collegiate Professor of Chemical Engineering and Director of the Hydrogen Energy Technology Laboratory at the University of Michigan. He also holds appointments in the University's Department of Mechanical Engineering and Applied Physics Programs. Dr. Thompson has distinguished himself in research in the areas of novel catalytic, electrocatalytic, and adsorbent materials. He is co-founder of T/J Technologies, a developer of nanomaterials for advanced batteries that was acquired by A123Systems in 2006, and more recently founded Inmatech to commercialize catalytic materials and processes discovered and developed in his University of Michigan laboratories. He is the Director of the Michigan-Louis Stokes Alliance for Minority Participation, a National Science Foundation funded program that teams the University of Michigan with other Michigan universities in an effort to significantly increase the number of minority students earning science, technology, engineering and mathematics baccalaureate degrees. He serves as Consulting Editor for the AIChe Journal and is a member of numerous technology committees and roundtables. Professor Thompson has authored more than 200 publications and has been awarded ten patents. He received his Ph.D. and M.S.E. in Chemical Engineering from the University of Michigan, and his B.ChE from the University of Delaware.

Dr. John Turner, Research Fellow, National Renewable Energy Laboratory
Dr. Turner is an internationally recognized expert in the field of hydrogen production via photoelectrochemical splitting of water, and has also made important contributions in the development of novel fuel cell components. His monolithic photovoltaic-photoelectrochemical device continues to hold the world-record efficiency for solar water splitting (>12% direct solar to hydrogen conversion efficiency). Other work involves the study of electrode materials for high energy density lithium batteries and fundamental processes of charge transfer at semiconductor electrodes. He has authored or co-authored more than 140 technical publications, He received the Hydrogen Technical Advisory Committee (HTAC) award for Research Excellence in 1999, twice received the Midwestern Research Institute President's Award for Exceptional Performance in Research, the Idaho State University Outstanding Achievement Award and received the U.S. DOE Office of Science Outstanding Mentor

Award in 2005, 2007, 2008, 2009 and 2010. He is the Editor of the Journal of Renewable and Sustainable Energy (an AIP journal), and a Fellow at the Renewable and Sustainable Energy Institute. He received his B.S. from Idaho State University, his Ph.D. from Colorado State University, and completed a postdoctoral appointment at the California Institute of Technology before joining NREL in 1979.

Dr. Yong Wang, Laboratory Fellow, Pacific Northwest National Laboratory
Dr. Wang has served as the Pacific Northwest National Laboratory's (PNNL) Associate Director of the Institute for Integrated Catalysis since 2008, and led the Catalysis and Reaction Engineering Team from 2000 to 2007. Concurrent with his position at PNNL, he holds a joint appointment at Washington State University, where he is the Voiland Distinguished Professor in Chemical Engineering. Dr. Wang is an internationally-recognized leader in the development of novel catalytic materials and reaction engineering for the conversion of fossil and biomass feedstocks to fuels and chemicals. He has authored more than 130 peer reviewed publications and is the inventor numerous catalytic technologies, resulting in more than 150 patents. He received a Ph.D. and M.S. in Chemical Engineering from Washington State University and an M.S. and B.S. in Chemical Engineering from the Chengdu University of Science and Technology, China.

Dr. Alan Weimer, H.T. Sears Professor, Department of Chemical & Biological Engineering, University of Colorado
In addition to being an endowed Professor in the University of Colorado at Boulder's (CU) Department of Chemical & Biological Engineering, Dr. Weimer is also the Executive Director of the Colorado Center for Biorefining and Biofuels located at CU. Previously he worked as a research scientist for over 15 years at the Dow Chemical Company in Midland, Michigan. Dr. Weimer's numerous awards include the Excellence in Bio-Derived Technology Commercialization Award from the Colorado Cleantech Industry Association in 2010, the AIChE Excellence in Process Development Research Award in 2010, the University of Colorado Physical Science Company of the Year Award (Sundrop Fuels) in 2009, and the Dow Chemical Company Research Inventor of the Year Award in 1993. He received his Ph.D. and M.S. in Chemical Engineering at the University of Colorado and his B.S. at University of Cincinnati.

Daryl Wilson, Chief Executive Officer and President, Hydrogenics
Mr. Wilson has been the Chief Executive Officer and President of Hydrogenics since December 2006, and has served as the Director of ATS Automation Tooling Systems Inc. since February 2009. Hydrogenics is a Canadian company with over 60 years of experience designing, manufacturing, building, and installing industrial and commercial hydrogen systems around the world, with over 1,800 units installed in over 100 countries. His 25-year background in technology and industrial management has included experience in operations, manufacturing, human resources, product research and development, and organizational change and turn-around. Prior to joining Hydrogenics, Mr. Wilson held numerous senior leadership positions, including Senior Vice President of Manufacturing, Engineering and Development Divisions of Royal Group, Inc.; Vice President of Manufacturing Operations Divisions of ZENON; and Vice President of Manufacturing at Toyota Motor Manufacturing Canada, Inc. He holds a B.S. in Chemical Engineering from the University of Toronto and earned an M.B.A. in Operations Management/ Management Science from McMaster University.

Appendix C

An Invitation Letter from U.S. Secretary of Energy Dr. Steven Chu to Dr. Levi Thompson, Chair of the Hydrogen Production Expert Panel

The Secretary of Energy
Washington, DC 20585

May 2, 2012

Dr. Levi Thompson
Richard E. Balzhiser Collegiate
Professor of Chemical Engineering
University of Michigan
3230 H. H. Dow Building
2300 Hayward Street
Ann Arbor, Michigan 48109

Dear Dr. Thompson:

As part of President Obama's all-of-the-above energy strategy to reduce America's reliance on foreign oil and address gas prices, I am pleased to invite you to the Department of Energy's (DOE) Expert Panel Workshop to assess critical research needs for affordable production of hydrogen, particularly in view of the increased availability of low cost natural gas. While the Department is focusing on battery technologies, hydrogen and fuel cells still remain a part of our diverse portfolio, and I recognize industry's continued investment and recent progress in these areas.

The Hydrogen Production Expert Panel, comprised of leading visionaries from industry, academia and national laboratories, is being convened as a subcommittee of the Department's Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) on May 10-12, 2012, in the Washington DC area. HTAC is a DOE advisory committee that is chartered in accordance with Federal Advisory Committee Act, 5 U.S.C. App. 2.

The goals of the workshop are to develop recommendations for HTAC regarding how DOE should prioritize the research and development (R&D) needs for advancing hydrogen technologies for both near-term and long-term markets, and to formulate strategies for leveraging R&D collaborations across DOE programs and other Federal agencies.

I am always excited by the advancements through American ingenuity and how we continue to make strides in reducing our carbon footprint through advanced energy technologies. Given that hydrogen can be a key contributor for energy storage, production of electro-fuels, and clean efficient transportation, your recommendations on potential future R&D needs would be highly valuable. Further details on the Hydrogen Production Expert Panel Workshop will be provided by HTAC management. I look forward to your participation.

Please feel free to contact Dr. Sunita Satyapal, Program Manager, Fuel Cell Technologies Program, at (202) 586-2336, if you have any questions.

Sincerely,

Steven Chu

Appendix D

A Perspective on Hydrogen Production

Presented to the Hydrogen Production Expert Panel
May 10, 2012

Dr. Lawrence D. Burns

Professor of Engineering Practice
University of Michigan

Director of the Program on Sustainable Mobility
Columbia University

ABSTRACT

This paper provides a perspective on hydrogen production based on the drivers of transformational change and how hydrogen might create value in the future economy. While we are swimming in a sea of creative disruption, our energy and transportation systems have changed only incrementally over the last century despite promising technology and troubling side effects. Necessary conditions for transformational change in these sectors are identified and recommendations for near and long term hydrogen production are provided based on these conditions. Specifically, the future of hydrogen production should

- Be framed in the context of value creation and integrated energy systems, not on a stand-alone basis
- Be judged in terms of system metrics and targets focused on how value is derived from hydrogen, not simply in terms of the cost, efficiency and CO2 emissions of different supply chains
- Encompass fossil and renewable feed-stocks for hydrogen jointly and avoid prematurely dismissing options
- Recognize the interdependence of hydrogen demand and the devices that use hydrogen to create value (e.g., more fuel cell electric vehicles leads to more hydrogen demand which leads to more hydrogen supply which leads to more fuel cell electric vehicles)
- Realize that hydrogen from natural gas in the near term will help establish a market demand for hydrogen from renewable sources in the long term
- Comprehend market “tipping points” as a necessary condition for large scale market penetration and target them with fast, efficient learning cycles (markets tip when consumer value > market price > supplier cost)
- View hydrogen and its uses as one of many promising opportunities, not as the sole answer for the future, or simply a competitive alternative to other energy carriers

INTRODUCTION

This paper shares my perspective on hydrogen production and its importance to the future of energy and transportation in the United States. It emerged from a request by Levi Thompson, Bob Shaw and Eric Miller to help motivate and frame the work of the Hydrogen Production Expert Panel organized by the Federal Hydrogen and Fuel Cell Technology Advisory Committee (HTAC).

Hydrogen plays an important role in the world's economy today and appears destined to play an even more important role. Momentum is building worldwide for broader uses of hydrogen on a larger scale. For example,

- Hydrogen is essential to convert tar sands and heavy hydrocarbons into modern and cleaner fuels
- Hydrogen is being produced from surplus wind energy and stored in salt caverns for future use
- Combined heat, hydrogen and power systems (CHHP) are being developed to make more efficient use of natural gas
- Hydrogen is being distributed and stored in natural gas pipelines
- Several automakers (e.g., Daimler, GM, Honda, Hyundai, Nissan and Toyota) have signaled their intentions to market commercial fuel cell electric vehicles in 2013 to 2016 and Germany, Korea, the United Kingdom and Japan have committed to deploying hydrogen stations for these vehicles
- Japan is exploring the use of bi-product hydrogen from steel manufacturing for a variety of purposes

These examples are in addition to today's already important uses of hydrogen in refineries, chemical plants and ammonia/fertilizer production.

Because of its geographic size, the inertia of its installed energy and transportation systems, and strong vested interests in these systems, the US faces significant challenges transitioning to an economy that is increasingly dependent on hydrogen. At the same time, the U.S. has much to lose in terms of energy economics, national security, geo-political leverage, and economic growth by falling behind. There is significant first-mover advantage in owning transformational technologies, in gaining real world know-how and in developing an experienced workforce. We witnessed this during the industrial revolution and we see it today in the enormous success of companies like Apple, Google, Microsoft and Intel.

Clearly, the contributions of the Hydrogen Production Expert Panel will prove timely for the U.S. and I am pleased to have an opportunity to help frame this initiative.

We tend to view things through lenses shaped by our experiences and interpret what we see in a context based on our knowledge and beliefs. This means several people can view the same things and reach different conclusions. Such diversity can be useful in preparing for the future.

How I see and interpret the world is influenced by my past experiences as General Motors Vice President of Research & Development and Planning from 1998-2009, and my ongoing experiences as

- Professor of Engineering Practice, College of Engineering, University of Michigan
- Director, Program on Sustainable Mobility, The Earth Institute, Columbia University
- Senior Advisor to the Chairman, Hess Corporation
- Consultant, Google Inc.
- Vice Chairman, MRIGlobal (a not-for-profit company responsible for co-managing the National Renewable Energy Laboratory)
- Member, Advisory Council, VantagePoint Capital Partners
- Member, Advisory Council, GreenTech Capital Advisors
- Member, Advisory Board, Kitson & Partners (an innovative real estate developer)

Taken together, my GM and "encore" careers have provided both a wide-angle lens and a microscope for viewing what is occurring on several fronts. This paper shares what I see related to

- Transformational change
- Energy and transportation
- Hydrogen infrastructure and fuel cell electric vehicles
- Hydrogen production

It then interprets what I see to help frame the important work of the Hydrogen Production Expert Panel.

TRANSFORMATIONAL CHANGE

Transformational change fundamentally alters an entire system and redefines how it behaves. It creates a new future that has never existed before and results in new assumptions, beliefs, principles, patterns, and rules for understanding system behavior and dynamics. In contrast to incremental change, which occurs within the confines of past experience and can often be modeled and predicted, transformational change is typically disruptive and hard to forecast.

From my vantage point, I see the following

1. Transformational change has already disrupted several industries and is in the process of disrupting many more
2. Transformational change is often due to a combination of technology and business model innovation
3. Value creation is being transformed by design and process innovation focused on delivering compelling consumer experiences
4. Incumbents are inherently at a disadvantage and typically do poorly when confronted with transformational change
5. Today's "grand challenges" are rooted in systems-of-systems with huge inertia (i.e., they are "wicked" problems)
6. New commercial "eco-systems" are often needed before markets adopt new technology
7. Communities have the opportunity to redefine public goods using technology and governance/business models that simultaneously offer better services at lower cost

While each snapshot is interesting to reflect on alone, when viewed as a photo album they suggest something significant might be taking place. Moreover, when combined to form a collage, a profound picture emerges that should not be ignored.

One's interpretation of this picture depends on one's perspective. When I "connect the dots," I see a world characterized by rapid and disruptive change that is transforming how people lead their everyday lives and how enterprises and individuals create value. Whether one calls this "Disruptive Innovation," "Creative Disruption," the "Innovation Economy" or the "Experience Economy," it is clear that *the world is not flat*! Instead, our future is being defined by change that is *non-linear, dynamic and uncertain*. Preparing for this future requires more than continuous improvement. It also calls for bold initiatives that create the future, not just respond to it.

The future of energy and transportation is being defined within this setting of widespread transformational change. This is one reason why the work of the Hydrogen Production Expert Panel is important. Hydrogen production is an essential part of a larger system that promises to transform how we interact economically and socially. We must understand hydrogen production in the context of how hydrogen will help create value in the future economy.

By examining several examples of transformational change, I have concluded the following are necessary to make it happen

- The total system must be comprehended
- Commercial eco-systems encompassing several industries must be changed together
- Market tipping points must be reached wherein consumer value > market price > supplier cost
- Focus must be placed on enhancing consumer experiences (to increase value) and supplier processes (to reduce cost and improve quality)
- Fast and efficient learning cycles with real products and real consumers must be pursued at the right scale

Applying these conditions to energy and transportation in general, and hydrogen infrastructure and fuel cell electric vehicles specifically, helps frame how we should approach the future of hydrogen production.

ENERGY AND TRANSPORTATION

For the most part, the U.S. energy and transportation (excluding air) systems have had the same fundamental "DNA" for over a century. While they have continuously improved incrementally, they have not fundamentally transformed the way several other industries have (for example, the information, communications, publishing, media, pharmaceutical and photography industries).

Globalization, negative side effects and maturing new technology all suggest energy and transportation are ripe for transformational change. ***Why hasn't it occurred?*** I believe the answer is because these systems

1. Are highly complex with extensive interdependencies among their components
2. Depend on each other to deliver consumer value

3. Have huge inertia
4. Are driven by multiple objectives (economic growth, jobs growth, national security, sustainability, freedom, …)
5. Have strong vested interests that either resist change or seek to bias change
6. Have been steered with inconsistent purpose
7. Are addressed with individual technologies and by individual sectors when
    - the value of one technology often depends on other technologies (we get trapped into arguing technology A is better than technology B when A and B together generally trump A or B alone)
    - our daily lives seamlessly touch many sectors interdependently

Based on a campus-wide energy systems and policy seminar I co-led at University of Michigan last year, I have concluded that our energy challenge is not due to a lack of resources or knowledge. Plenty of raw energy exists to grow the world's economies and plenty of technology exists to do so sustainably. Instead, our energy challenge is due to

- A lack of integrated systems
- The enormous inertia of the installed base
- Leadership that is driven by vested interests

By combining our abundant fossil and renewable energy resources with a broad portfolio of promising technology, integrated system opportunities surface with the potential to excite consumers, reward investors and enable sustainable development.

Transformational change is within reach for energy and transportation. But, we must pursue it in the context of

- How we live our daily lives
- Integrated systems
- Creating compelling customer experiences based on new technology
- Focusing on market tipping points by learning fast, efficiently and robustly
- Thinking and acting holistically with a common understanding and collective will

HYDROGEN AND FUEL CELLS

Fuel cell electric vehicles (FCEVs) using hydrogen from a variety of sources are among the maturing technology promising to transform transportation and energy. There are a wide range of views on the ultimate potential, timetable and importance of FCEVs and the viability of a hydrogen infrastructure to enable them.

Based on my hands-on experience leading GM's fuel cell program for over a decade and my continued involvement with this technology since leaving GM, FCEVs are ***real!*** Compelling evidence suggests others share my view. For example, why would Daimler, GM, Honda, Hyundai and Toyota all continue costly FCEV development programs over the past four years, amidst a severe auto industry recession and the launch of highly incentivized plug-in electric vehicles, if they did not feel this technology holds ***real*** promise? The answer is because they believe they can ultimately supply FCEVs that are marketable, affordable, durable, sustainable and profitable. For consumers, FCEVs will be

- Safe
- Family-sized
- Refuel fast (5 to 10 minutes)
- Have acceptable range (>300 miles)
- Have pleasing electric drive attributes
- Cost no more than vehicles with other technologies meeting future regulations

Several OEMS are indicating they have advanced to the point where the remaining challenges can only be addressed through market-based learning cycles with real customers using commercially designed and engineered FCEVs. In fact, Hyundai stated they will start this dynamic in 2013.

These auto companies can't take this step alone. To create value with FCEVs, hydrogen must be safely, conveniently and affordably available. Just like today's roadway transportation system, auto companies must co-exist with energy companies in a commercial eco-system for consumers to realize value from fuel cells and hydrogen. The good news is that it appears the required hydrogen infrastructure for FCEVs is also ***real!*** Hydrogen produced from natural gas (either at a station or delivered to a station) is cost competitive on a "gasoline gallon equivalence" (gge) basis given today's oil and natural prices. And, my "farmer's math" suggests the U.S. can get off imported OPEC oil with just over a 10% increase in natural gas demand if this natural gas is reformed to make hydrogen for FCEVs. The issue is not the availability of alternatives to oil for transportation in the U.S. Instead, it is the lack of vehicles that can use these alternatives.

So, we have reached a critical juncture, which is not surprising given the necessary conditions for transforming complex systems with co-dependence. For FCEVs to realize their full potential, hydrogen must be available to customers. And, for hydrogen to become available, FCEVs must exist to use it. But, this will only happen if commercial learning cycles are enabled for both the vehicles and the infrastructure. Clearly, we must transition both the auto industry and energy industry together and this is hard to do in light of the strong vested interests that exist in the current system.

To break this log-jam, auto companies, energy companies and governments must work together to efficiently and quickly reach the market tipping point for FCEVs using hydrogen. In essence, to create value, we must deploy a customer-centric commercial system based on FCEVs and hydrogen. Germany is providing a good example of how this can be done. Hopefully, the U.S. will muster the collective will to follow Germany's lead.

My "farmer's math" also suggests that the hydrogen infrastructure investment to support first generation commercial FCEVs is on the order of 1/50th the investment already made by auto companies. Together, auto companies will likely have invested on the order of $10B to position to deploy commercial FCEVs. The first 50,000 FCEVs will use about 50,000 kg of H2 per day. This is 200 stations at 250 kg per day. At $1M per station, this is $200M, a relatively small investment to take the required learning to the next level.

HYDROGEN PRODUCTION

A lot of hydrogen is already being produced today in a variety of ways (steam/methane reforming, electrolysis, bio-hydrogen) and for many value adding uses (e.g., oil refining, fertilizer, chemicals, forklift trucks). Based on its attributes and where the world appears headed, we will very likely need significantly more hydrogen in the future for a wider variety of purposes. Many supply chains will compete to produce hydrogen from a variety of feed-stocks in a variety of ways at a variety of scales for a variety of purposes and a variety of consumers. Such competition is healthy. The Hydrogen Production Expert Panel will help us prepare for this future by enabling a common understanding of the future of hydrogen production.

As the panel goes about its work, I recommend we ask

- What is the system within which hydrogen production exists and what value does hydrogen provide in this system?
- How does this system impact hydrogen production and how does hydrogen production impact the system?
- How should we judge the value of hydrogen (metrics and targets)?

I also suggest that we don't just scientifically explore ways to produce hydrogen. While this is important, we also need to innovate in the context of the entire required commercial eco-system. Hydrogen needs to be produced, stored, distributed and converted to create value, and how it is produced should comprehend the other steps in this value supply chain. For example, because hydrogen is difficult to distribute, there are advantages to producing at smaller scale and close to points of use.

I also recommend that we be careful to not prematurely dismiss options for producing hydrogen. You never know where an option might lead, especially in a system context. For example, producing hydrogen from surplus wind electricity via electrolysis and distributing/storing it in natural gas pipelines may prove to be of value. This option should not be dismissed solely on an efficiency basis.

We must also recognize that it is going to be very difficult to realize significant CO2 reduction in road transportation without electrically driven vehicles. We will need to transition the U.S. car fleet to have a significant mix of these vehicles and natural gas appears to be a good source of hydrogen (and electricity) to stimulate this mix. Therefore, we should not dismiss natural gas as a source of hydrogen simply because it is a fossil fuel and results in CO2 (albeit much less per mile when used for hydrogen in FCEVs or electricity in plug-in EVs). Instead we need to create an upward growth spiral for hydrogen by combining fossil and renewable energy sources systematically and synergistically.

The panel should focus on producing hydrogen in a system context to meet today's needs and to reach market tipping points. It should also focus on innovation to enable more applications and greater supply more sustainably.

I specifically recommend the future of hydrogen production should

- Be framed in the context of integrated energy systems, not on a stand-alone basis
- Be judged in terms of system metrics and targets focused on how value is derived from hydrogen, not simply in terms of the cost, efficiency and CO2 emissions of different supply chains
- Encompass fossil and renewable feed-stocks for hydrogen together and avoid prematurely dismissing options
- Recognize the interdependence of hydrogen demand and the devices that use hydrogen to create value (e.g., more fuel cell electric vehicles leads to more hydrogen demand which leads to more hydrogen supply which leads to more fuel cell electric vehicles)
- Realize that hydrogen from natural gas in the near term will help establish a market demand for hydrogen from renewable sources in the long term
- Comprehend market "tipping points" as a necessary condition for large scale market penetration and target them with fast, efficient learning cycles (markets tip when consumer value > market price > supplier cost)
- View hydrogen and its uses as one of many promising opportunities, not as the sole answer for the future

CLOSING

In the ***near-term***, let's deploy an initial hydrogen infrastructure in sync with auto company plans to deploy commercial FCEVs. First generation commercialization is essential to begin creating consumer value that will lead to the required commercial eco-system needed to reach a market tipping point.

In the ***mid-term***, let's be sure we reach a market tipping point based on the value sweet spots for hydrogen in a system context.

In the ***long-term***, let's pursue new ideas in anticipation of a much larger future market for hydrogen as a key component of the energy, transportation and economic systems defining how we will live our daily lives.

For sure, hydrogen is not the sole answer and offers little value on a stand-alone basis. Therefore, we should avoid frictional losses by debating whether hydrogen is a better energy carrier than electricity. Both are important and the fact that hydrogen can produce electricity and electricity can produce hydrogen makes their value synergistic and their uses complementary.

Hydrogen's value is realized in terms of the role it plays in a broader system. It is not a source of energy. It is an energy carrier that must be produced, distributed, stored, and converted to deliver energy for power and heat. The fact that hydrogen can be produced from fossil, renewable and nuclear sources is an "and" synergy not an "or" trade-off.

For hydrogen to prove valuable, we need “apps” that use hydrogen. For such “apps” to exist, hydrogen must be available. To resolve this “chicken and egg” dilemma, we must collaborate and we must also have a rooster! Relative to hydrogen production, the Hydrogen Production Expert Panel has the opportunity to be the rooster.

Some say we cannot afford to do everything and that we must place our bets and try to pick winners. The Clinton/Gore Administration bet on hybrids. The Bush/Cheney Administration bet on hydrogen and fuel cell EVs. And, now the Obama/Biden Administration is betting on batteries and plug-in EVs.

The bottom-line is that we need all three and even more. The key is to learn fast and efficiently. The key is to focus initially on market tipping points to get to the ultimate end goal. The key is to view technologies as part of an integrated system, not on a stand-alone basis. This means it is best to bet on what I call the ***Power of “And”*** which is the sustainable energy and mobility future that results from thinking and acting holistically.

While there are no “silver bullet” solutions to the future of energy and transportation, it does appear hydrogen will play a bigger role in helping create value in the future economy. This means hydrogen production will be increasingly important. Germany, Korea, the UK and Japan have decided to pursue this opportunity more aggressively than the U.S. to improve the lives of their citizens through enhanced industrial competitiveness and energy security. They have clearly learned from the U.S. led industrial revolution regarding the importance of positioning for leadership.

I will end by sharing one last thing I am seeing that is very troubling to me and I am sure you. It is the lack of common understanding and collective will we have among our elected and appointed leaders on these subjects. I encourage all of us to keep asking “how can we work together to enable all promising technologies to quickly and efficiently realize their interdependent market “tipping points?” The Hydrogen Production Expert Panel has an important role to play here by providing a definitive statement on hydrogen production. Hopefully, our government leaders will listen to your findings and act on them accordingly.

Appendix E

Hydrogen Production Expert Panel Presentations

HPEP Vision & Process:

Dr. Levi Thompson, Chair, Hydrogen Production Expert Panel

H_2 Production Expert Panel Workshop

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

Enabling a path forward for the widespread production of affordable renewable hydrogen for future energy scenarios

EXPERT PANEL GOALS

- **EVALUATE** the status and prospects for hydrogen production, quantifying supply and demand in current markets and in possible future scenarios (energy, transportation, chemicals and fuels, etc.)
- **IDENTIFY** the key technologies and critical challenges in producing hydrogen for today's markets, and for large-scale central and distributed renewable production
- **PRIORITIZE** research and development needs to advance promising hydrogen production technologies
- **STRATEGIZE** on how to best leverage R&D efforts in hydrogen production among DOE Offices and Programs (including EERE-FCT, SC, ARPA-E and the Innovation Hubs), and with other agencies

WORKSHOP PROCESS

Panel Steering Committee with broad spectrum of expertise oversees workshop flow and report generation

↓

Panel Technical Experts present on opportunities and challenges in near-term to long-term H_2 production technologies

↓

Breakout sessions of Panelists and invited stakeholders identify key challenges and research priorities in near- and long-term technologies

↓

***WORKSHOP PRODUCT:** Report draft- published online for public feedback before incorporation into final version for HTAC approval, and submission to DOE*

H_2 Production Expert Panelist Roles

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

"Steering Committee" and "Technical Experts" work together to meet goals

PANEL STEERING COMMITTEE *offers leadership and experience, overseeing workshop flow and report generation, including Q&A with Technical Expert Presenters, and information exchange at breakout sessions.*

PANEL TECHNICAL EXPERTS *offer specialized expertise, presenting on status, challenges, opportunities and recommendations in a spectrum of near-term to long-term H_2 production technologies.*

Q&A DISCUSSIONS EXPECTED TO COVER A BROAD SPECTRUM OF CRITICAL ISSUES:

Technology Status

- *Overview and major embodiments of hydrogen production technologies (reforming, thermolytic, eletrolytic, phototytic, etc.)*

Challenges

- *Market and business forces: including costs of production, infrastructure, dispensing, etc., and energy and materials resources and feedstocks*
- *Technology barriers: manufacturing, engineering; device level performance and durability , fundamental science barriers.*
- *Policy barriers and impact of codes and standards*

Opportunities

- *Investment Resources: Industry and venture capitalists; Federal , State , International resources and investments*
- *Policy Resources: government commissions (HTAC, USDRIVE, CEC, etc.); lobbying agencies, Industry boards and consortia, etc.*
- *R&D Resources: Internal industry R&D , national / international laboratories; universities and academia; Research consortia, etc.*
- *Leveraging common interests and progress in chemicals /fuels production, transportation technologies, stationary power, energy storage, etc.*
- *Leveraging market needs and resource trends: hydro-cracking needs in fuels processing, natural gas boom, etc.*

Insights and Recommendations.

- *Leaders from industry, academia and the national laboratories sharing their unique perspectives on hydrogen production technologies*

Addressing the H2 Production Challenges

Distributed Natural Gas Reforming

DoE Hydrogen Production Expert Panel

Arlington, VA, 05/12/2012 I Dengel, Udo I Air Liquide Global E&C Solutions

Technology Status – distributed Natural Gas Reforming

- *First “onsite” SMR installations at beginning of last decade*
- *Today technology is commercially available, range 50 - 2500 kg of H2/day*
- *Majority of installations are industrial users: metals, electronics, glass, chemicals*
- *Where Natural Gas is available, onsite SMR competes with gaseous or liquid H2 by truck*

Air Liquide’s HYOS-R 10k 170 - 580 kg/day of H2

Challenges – distributed Natural Gas Reforming – 1 of 2

- *High capital costs*
  - *reduce costs through higher production volumes/economies of scale*
  - *for market to demand large number of onsite SMR units will take time*
  - *in developed economies, competition against established distribution is challenging, especially if location is close to central H2 source => limits opportunities to the fringes of the distribution network*
  - *in US currently a lot of idle liquid H2 generation capacity - makes onsite H2 less competitive*

- *Feedstock variability*
  - *Natural Gas and LPG are proven feedstocks*
  - *Alternative feedstocks (biogas) still need work*

- *For vehicle fueling stations demand is at low end of capacity range <200kg/day*
  - *Means high Capex ratio and fewer onsite SMR for vehicle fueling applications*
  - *No standard methodology to measure H2 purity for fuel cell applications - J2719*
  - *Variability of H2 demand requires either storage or turn down => high Capex*

Challenges – distributed Natural Gas Reforming – 2 of 2

- *Technical complexity of operating/maintaining the SMR equipment still high compared to other equipment used in a traditional fueling station*
  - *Dealing with pressure, heat, chemical processing - equipment and codes/regulation require qualified personnel to monitor & maintain*

- *"Chicken and Egg" issue - even if we solve H2 production, the lack of H2 vehicles and dispensing infrastructure will limit growth of H2 Energy sector*
  - *H2 production represents only a share of overall cost*
  - *Long term, cohesive government strategy would help*

Opportunities – distributed Natural Gas Reforming

- *Developing economies will drive demand for onsite SMRs for industrial use*
  - *Will help to increase production volume/economies of scale*
- *In developed economies "trigeneration" could lead to additional demand*
  - *Combining stationary power + H2 + heating or cooling can increase number of installations/production volume*
- *Improvements in costs and operability will continue as technology matures and number of installations grows*
- *Low Natural Gas in prices in US gas will contribute to lower Opex*
- *As CNG use for vehicle applications spreads it can serve as building block for H2 infrastructure*
  - *fueling stations will have NG connection and handle compressed gas*

Recommendations - distributed Natural Gas Reforming

- *R&D*
  - *Improve design to increase energy efficiency*
  - *Lower feedstock variability*
  - *Continue to invest in material development (catalyst, construction materials) to improve performance and reduce cost*
- *Operations & business case*
  - *Continue to increase reliability and operability of system*
  - *Adapt system to variable demand – optimize combination of reformer and storage*
  - *Support development of "trigeneration" applications*
- *Policy*
  - *Harmonize codes & standards for H2 fueling stations to simplify installation and lower project execution costs*
  - *To support biogas use for H2 fueling ensure decoupling of biogas location from H2 use location through biogas credits applied to use of pipeline NG for onsite SMR*
  - *Develop long term strategy from government for pathway to H2 infrastructure*

AIR LIQUIDE

Thank you for your attention

HYDROGEN PRODUCTION & SUPPLY

MANAGING THROUGH THE TRANSPORTATION MARKET TRANSITION

Department of Energy (DOE)
Hydrogen Production Expert Panel (HPEP)

Brian Bonner
May 11, 2012

AIR PRODUCTS

Infrastructure Transition

TODAY — PATHWAY — **FUTURE**

Hydrocarbon sourced infrastructure exists

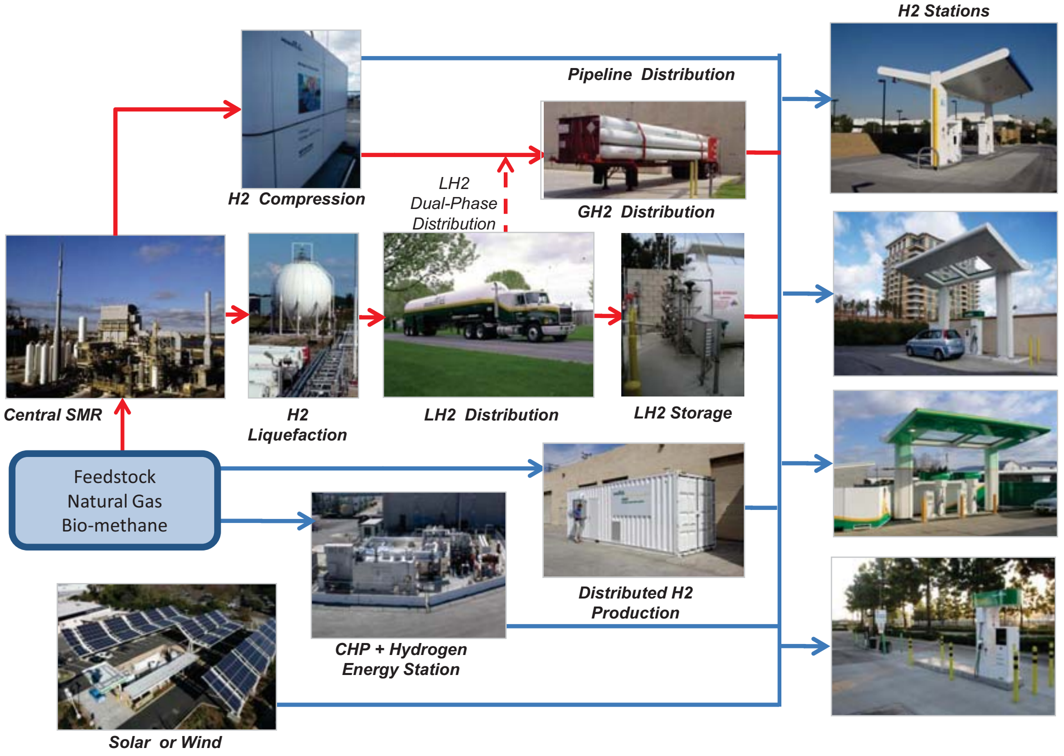
- **US production: 11 million tons/yr of H2**
- **Industrial applications 5%**
- **Refinery/chemical applications 95%**
- **US needs ~70 MM tons/yr to support 300MM vehicles**

Revise energy portfolio

Renewables, coal, nuclear, sourced H2 for transportation sector

AIR PRODUCTS

Hydrogen Supply Pathway Options



H2 Stations

Pipeline Distribution

H2 Compression

LH2 Dual-Phase Distribution

GH2 Distribution

Central SMR

H2 Liquefaction

LH2 Distribution

LH2 Storage

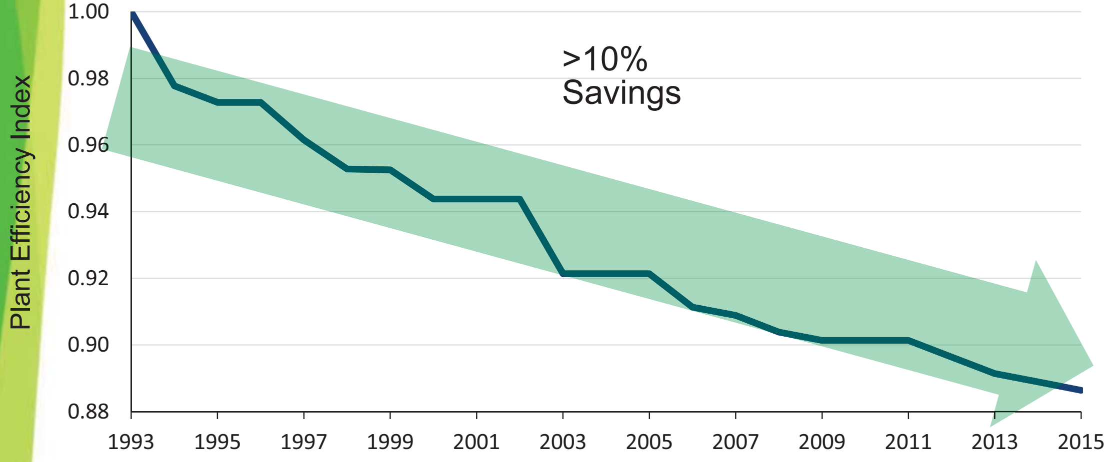
Feedstock
Natural Gas
Bio-methane

Distributed H2 Production

CHP + Hydrogen Energy Station

Solar or Wind Electrolyses

Large Central SMR Plant Efficiency Continues to Improve



Evolution of the Hydrogen SMR flowsheet towards:

- Increased Efficiency
- Customers evolving needs for power (cogen) and steam
- Multiple feedstock's RFG, ROG, propane, butane, and naphtha

Integrated Pipeline Drives Efficiency and Reliability

>1 billion SCFD of capacity
>20 operating plants
>600 miles of pipeline driving

Major Delivery and Station Breakthrough

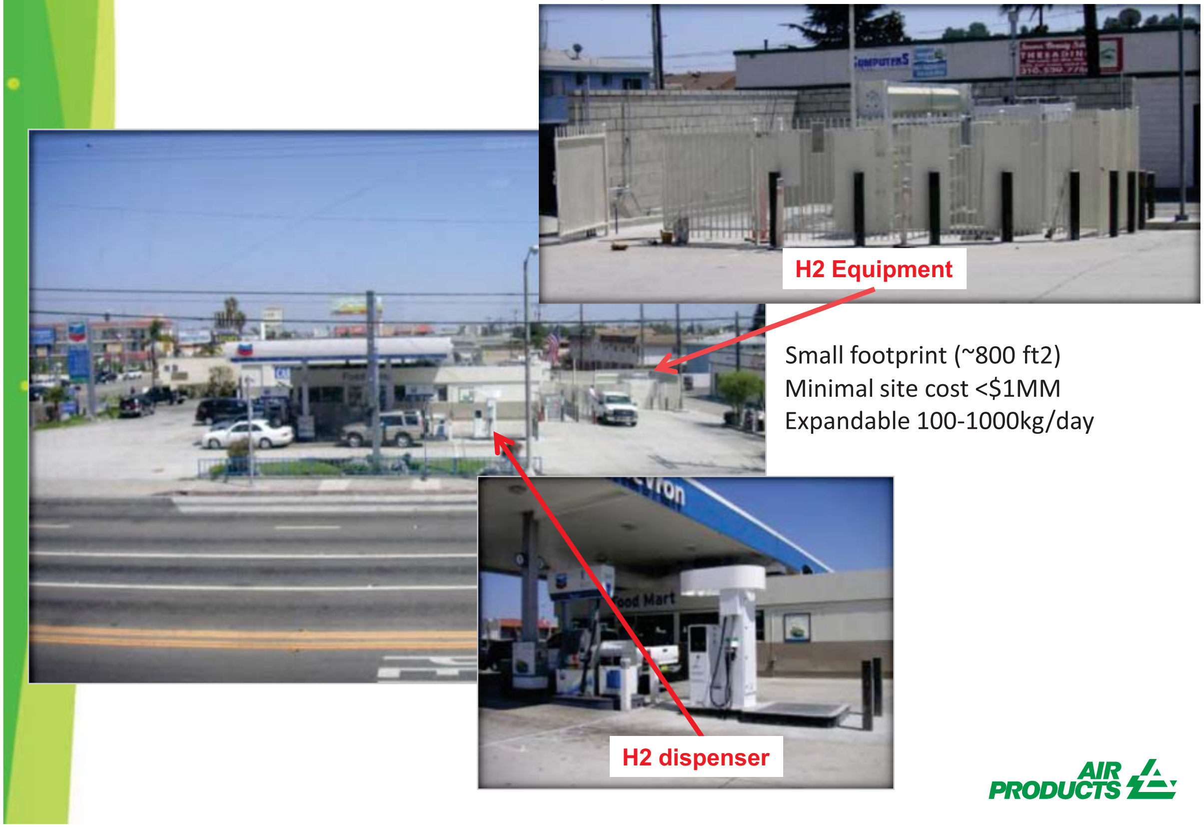
High Pressure Composite Bulk Storage. Multi-capable Liquid trailer

VS.

- Enables <u>step-change</u> in payload capacities, 3-4X via 7500psi delivered hydrogen.
- Enables distribution of hydrogen from all forms of distributed and renewable sources with minimum GHG emissions
- Promotes modular and expandable stations on existing gasoline forecourt.
- ELIMINATES ONSITE COMPRESSION for 350Bar. Minor compression for 700Bar.
- Technology extendable to 450/500bar.
- First deployed with DOD at DDWG. Operating in the U.S. for cell towers.

- Dual-Phase Hydrogen Delivery Trailer capable of delivering liquid and high pressure hydrogen up to 10,000 psi to a station.
- Enables <u>step-change</u> in liquid delivery to numerous applications.
- On the road in the U.S. and Europe.

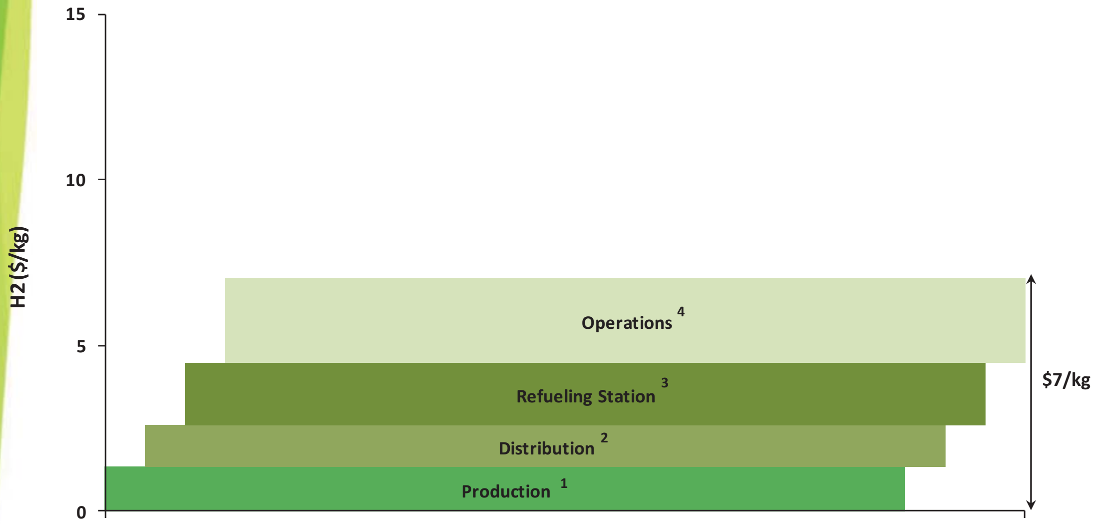
Harbor City H2 Station



Small footprint (~800 ft2)
Minimal site cost <$1MM
Expandable 100-1000kg/day

Commercial Hydrogen Refueling Cost Breakdown

200-300kg/day



1- NREL, Ruth et al 2009. Central SMR production
2- US DOE 10/2010. Infrastructure (Station with Tube Trailer Delivery)
3- APCI 2011 ($1.0 million hydrogen refueling station)
4- APCI/UCD 2011 ($250k/year.; Land rent, Operations & Maintenance, Insurance, Excise Tax)

Lessons Learned and Challenges

- Lessons Learned –DRIVE TO THE GASOLINE MODEL !
  - Use existing H2 and gasoline infrastructure
  - Traditional industrial gas technologies fall short
  - Improve delivery technologies
  - Reduced forecourt maintenance costs. Eliminate Compression!
  - Simple, modular, expandable stations
- Challenges
  - Prove the business case will incent private investment
  - Manage the customer/market through the growth cycle.
  - Renewable hydrogen supply slows down early market development and adds cost
  - Further drive down cost and expand supply base for technologies that can serve the market today !
  - The market is expecting 2015 commercialization of fuel cell vehicles. This may be our last chance!

AIR PRODUCTS

Thank You

AIR PRODUCTS

Hydrogen and fuel cell technical advisory committee meeting

May 11, 2012
Presented by: Prabhu Rao, VP Commercial Operations

Nuvera Fuel Cells
129 Concord Rd. Bldg 1
Billerica, MA 01821

Product Evolution

Nuvera has exploited engineering and manufacturing know-how to convert core hydrogen technologies into advanced energy products.

1st FC Stack (1993)

Forza C/A plant

Fiat FC Engine

PowerEdge

Core Enabling Technologies → **Integrated System Solutions** → **Sustainable Mobility Products**

Gasoline demo (1997)

Avanti (world class effy)

1st FP Module (1994)

PowerTap

H2 Generator (1998)

NG FPS

GASOLINE FPS

Nuvera - Market applications

Light Duty EV & Range Extender

Fuel Cell Forklifts

Ground Support Equipment

Industrial Mobility

Truck APU & Reefer

Fuel Cell Tractors

Transportation

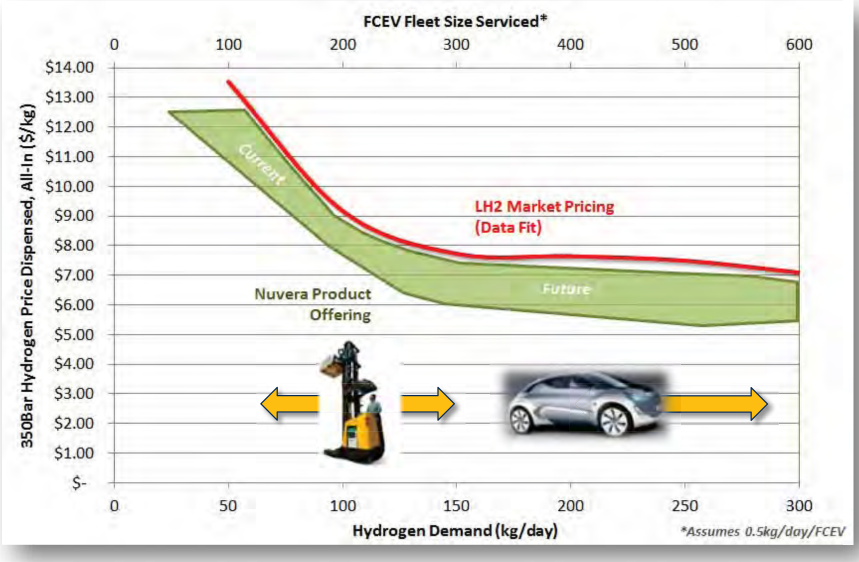
Fuel Cell Bus

Fuel Cell Vehicle

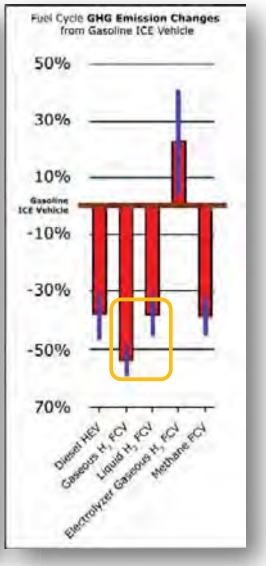
Aerospace APU

Hydrogen cost roadmap

PowerTap provides a low cost & greener solution



Comparison of Customer All-in H2 Costs, 350Bar Dispensed On-Site.
Ground storage and dispenser costs included. PowerTap assumes $0.06/kWh & $6/MMBtu NG, service and ROIC Included. Liquid H2 source from central plant and trucked to site, using existing LH2 equipment (sources: multiple gas producers)



Comparison of Well-to-wheel GHG Emission Pathways.
Source: ANL, M. Wang, 2002

Relative Scaling (Material Handling vs. Automotive)

Application	H2 Generator Peak Rating (kgH2/day)	H2 Generator Peak Rating (scfh)	Average H2 Refueling Station Production Capacity[1,2] (kg/day)	Maximum Vehicle Refuels per Day[3,4]	Average No. of FCV's Supported[4]	PTH 1X Storage Bank Scale Factor[6]	Maximum Class II Forklift Trucks Supported[2,7,8]
Small Community Station	56	~1000	38	10	92	1	13
Small-Medium Community Station	112	~2000	76	20	184	2	25
Medium-Large Community Station	280	~5000	189	50	461	5	64
Large Community Station	560	~10,000	379	100	921	9	127
Small Public Service Station	920	~16,000	622	164	1514	15	209
DOE Target Public Service Station	1500	~27,000	1014	267	2468	25	341

1. Assumes 69% Capacity Factor to account for seasonal & daily fluctuations in demand

2. Assumes 98% Station Availability (22days/yr with one 8-hr shift of service)

3. Assumes 80% Fuel Tank Oppurtunity Refills

4. Assumes 80-miles/gge FCV, 380-mile range & 12000-miles/year

5. Assumes 58% H2 gas utilization factor for cascade storage

6. Assumes 6500psig Cascade Storage, 3 Banks, 27 11-gal ASME cylinders, 20C ambient

7. Assumes 95% Capacity Factor for Material Handling

8. Assumes 1000Ah, 80% Discharge, 3 shift, 6 day/wk, 50 week/yr operation; RP = 52%effy

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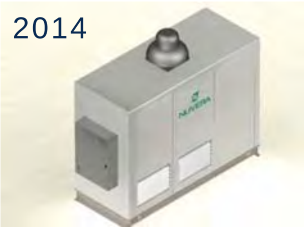
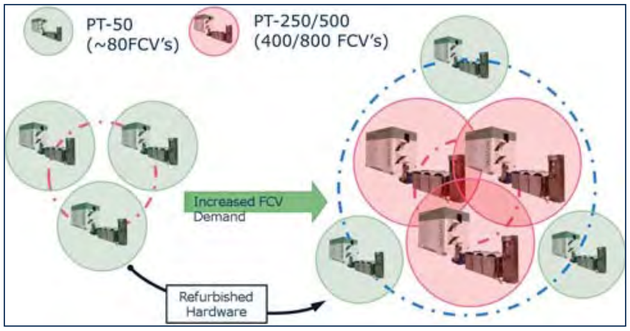
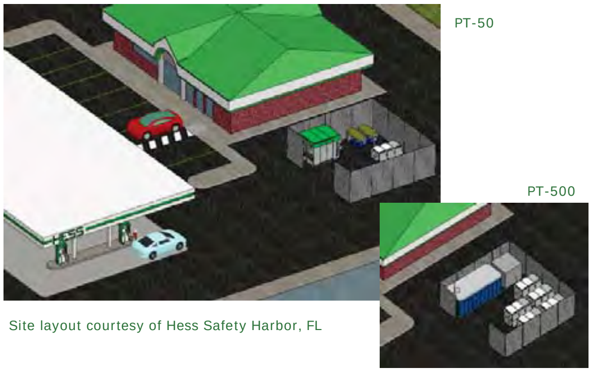
PowerTap Product Suite

PTG-50
(12' L x 4' W x 9' H)



PTG-250
(12' L x 6' W x 9' H)





Site layout courtesy of Hess Safety Harbor, FL

How can we Help the infrastructure rollout?

Current Products/Technologies – Onsite Generation (50-500 kg/day)

Challenge: Capacity Underutilization

Opportunities:

1. Promote multi application hydrogen use – material handling, vehicles, fleet refueling (GSE, Buses and refers) and merchant applications
2. Devise a financial vehicle to 'insure' against under utilization – ensure accountability of all stakeholders
3. Seek some alignment with NG infrastructure roll out

Future Products/Technologies – Onsite Generation (500-1500 kg/day)

Challenge: Capacity Underutilization + **Footprint**

Opportunities:

1. Fund development of compact SMR's, PSA's and Electrochemical Compressors – needed to ensure footprint

NUVERA FUEL CELLS

Nuvera Fuel Cells, Billerica, USA is ISO 9001: 2008 certified

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Near-term Opportunities for CHHP Technology

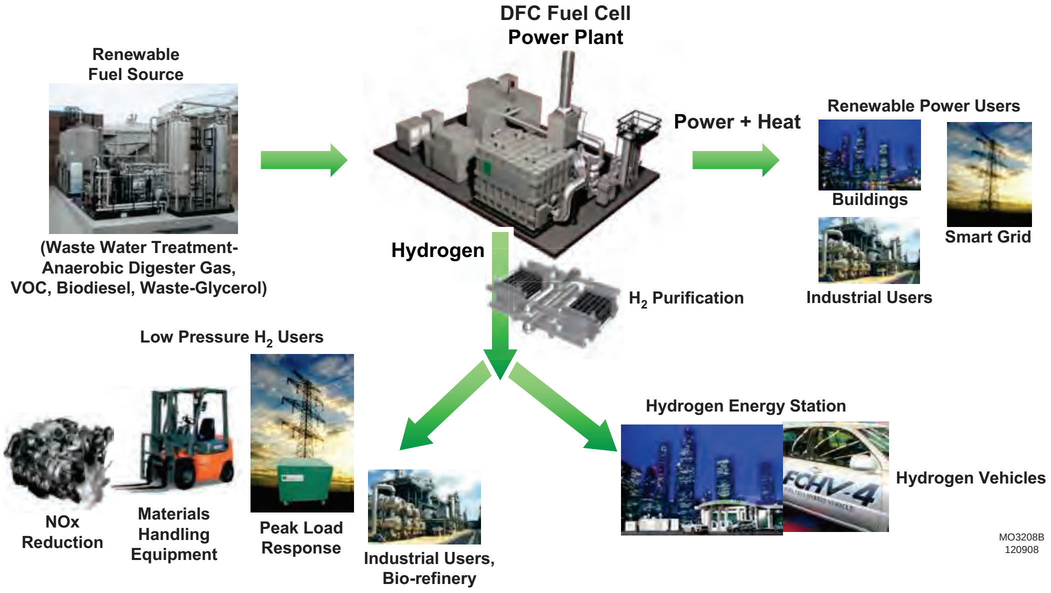
Pinakin Patel

Presentation for HTAC Meeting, Washington, DC

May 11, 2012

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Co-production of Renewable Hydrogen and Power



- **Co-production of Power and Hydrogen improves the Value Proposition**
- **Multiple hydrogen uses avoid stranded H_2 infrastructure assets**

What Can We Do With By-Product Hydrogen?

DFC300®

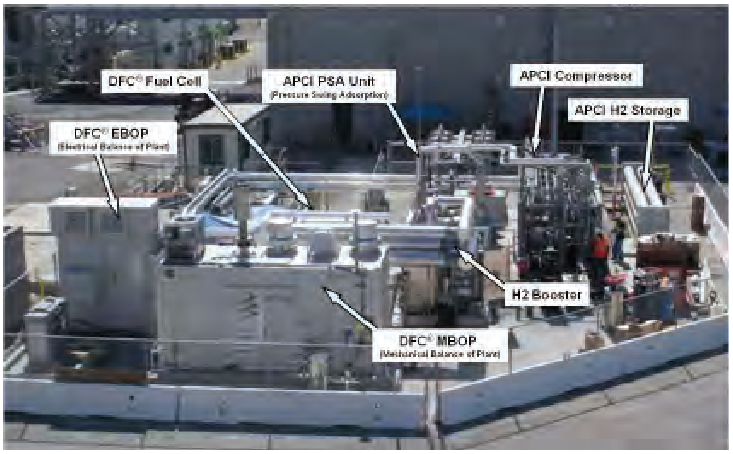
DFC1500®

DFC3000®

	DFC300®	DFC1500®	DFC3000®
Co-product			
Power, kW	250	1,150	2,300
Hydrogen, kg/day	**125**	**700**	**1,400**
Heat, mmBtu/hr	0.5	2.0	4.0
Refueling Capacity			
Cars, 4.2 kg/day	**30**	**140**	**280**
Buses, 25 kg/day	**5**	**24**	**48**
Fork Lifts, 2.1 kg/day	**60**	**280**	**560**
Plug-in Battery Hybrid, 12 kWh/day	**500**	**2,400**	**4,800**

MO3256A

Hydrogen Energy Station Fountain Valley, California



A joint venture between:

AIR PRODUCTS

National Fuel Cell Research Center
University of California, Irvine

California Environmental Protection Agency
AIR RESOURCES BOARD

FuelCell Energy

U.S. DEPARTMENT OF ENERGY

South Coast Air Quality Management District

Over 1 million kWh + 10,000 lb H_2 produced

Co-Production of Renewable Hydrogen in California

Orange County Sanitation District (OCSD)

Renewable H_2 Filling Station

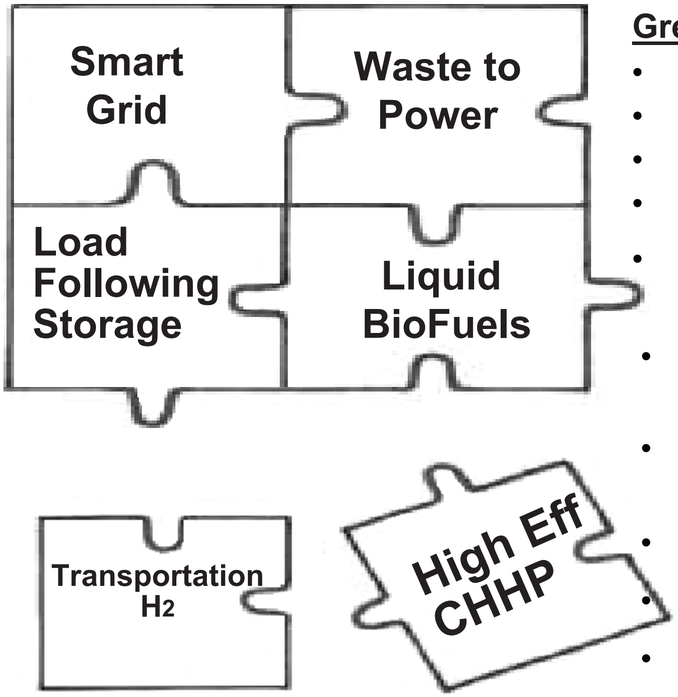
ADG fueled DFC-H2® Production Unit

- **Site load ~ 6 MW; up to 300 kW provided from fuel cell**
- **Engines on biogas reduced from 13 MW to <4 MW**
  - **due to NO_x constraints**
- **Potential using biogas fuel cell: 20 MW + 20 MW of peak power and kVAR support**

11.2 MW DFC® Power Plant – Largest in the World

- **This unit has a potential to co-produce over 5 tons/day H_2**
- **Hydrogen can be used to provide additional 11 MW of peak power for 8 hours per day**

Connecting Pieces of Energy Goals

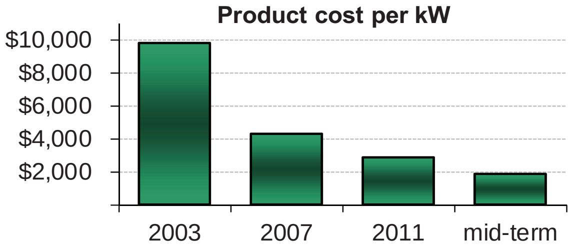


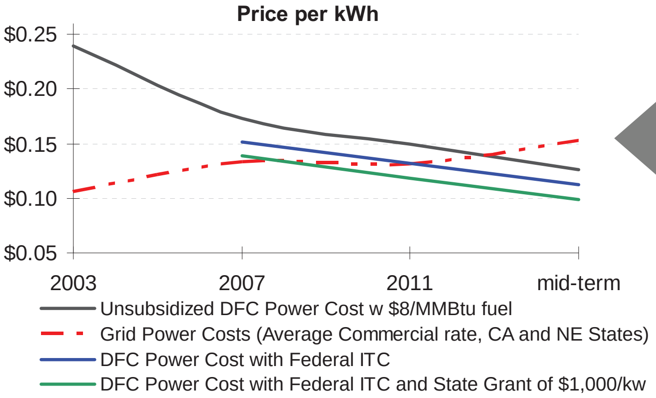
Green and Clean

- Maximize Renewable Energy
- Grid Stability
- Efficient Use of Fossil Fuels
- Clean Energy
- 11,000 GW Total ⟶ 400 GW ave
- National Security – reduce imports
- Gasoline ⟶ Ethanol BioButanol
- Diesel ⟶ BioDiesel
- Algae ⟶ Waste Biomass
- Crude BioOil ⟶ Needs H_2

CHHP Scale-up and Cost Reduction Needed

Product costs reduced >60% since first commercial installation in 2003





- DFC cost per kWh decreasing
- Grid costs increasing (i.e. investment in new capacity and transmission grid)
- Renewable biogas price per kW lower

Goal is to price below the grid, without incentives

Advanced Hydrogen Co-production Technology

DFC® Power Plant

(Electricity + Hydrogen)

→

Solid State Hydrogen Separator (EHS)

→

Solid State Hydrogen Compressor (EHC)

H_2 →

MO3145

Fuel Cell Cars

Materials Handling Equipment

Liquid Biofuels

Peak and Back-up Power

1 yr Factory Test at FCE

>1.5 yr Site Demo at OCSD

(DFC-H2-PSA)

100-cell baseline stack tested

Advanced CO-tolerant cell technology scaled up to 1000 cm^2 short stack

Single cell operated to 12,000 psi

Developing Strategic Alliance with Hydrogen Users

Thank you

Questions?

Pinakin Patel
Director of Special Systems and Research

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203-825-6072

PEM Electrolysis Summary

Dr. Katherine Ayers, Director of Research

PROTON
THE LEADER IN ON SITE GAS GENERATION

- Proton OnSite: World leader in hydrogen generation via proton exchange membrane (PEM) electrolysis: > 8 MW installed base worldwide
- Cost competitive in today's commercial markets for financial stability
- Significant opportunities for cost and efficiency improvements through fuel cell supply chain and technical progress
- Tremendous progress made in last 4 years despite policy obstacles; focus needed in the near term to commercialize demonstrated advancements

2000
S Series
1-2 Kg/day
13 Bar

2006
HPEM
0.5 Kg/day
138 Bar

2009
Outdoor HPEM
2 Kg/day
165 Bar

2010
C Series
65 Kg/day
30 Bar

We've Been Producing Great Products For More Than a Decade...

1999
GC
300-600ml/min
13 Bar

2003
H Series
4-12 Kg/day
30 Bar

2006
StableFlow®
Hydrogen Control
System

2010
Laboratory
Line

Commercial Status

- Firmly established products, markets and applications
  - >1800 fielded systems
  - Cost competitive today in commercial markets
  - $2B addressable power plant market alone

Power Plants

Heat Treating

Laboratories

Semiconductors

Government

- Demonstrated reliability and scalability
- Full solution provider: integration and containerization
- Fully developed manufacturing capability

PROTON
ON SITE

Technology Status

- Continuing to scale in pressure and capacity

28 cm^2
0.05 Nm^3/hr
Commercial

86 cm^2
2 Nm^3/hr
Commercial

210 cm^2, 10 Nm^3/hr
Commercial

550 cm^2, 30 Nm^3/hr
Pre Production

1100 cm^2, 90 Nm^3/hr
Concept

- Many pathways for large cost and efficiency impact
  - Potential for 50% to >90% reduction in highest cost components even at low production volumes
  - Multiple configurations demonstrate 74% LHV efficiency at 2 A/cm^2, 77% LHV efficiency at 1 A/cm^2

Challenges

- Government position impact on investment capital
- Unclear requirements for energy markets
- Inconsistent funding stream impact on R&D efficiency
- Lack of coordination with fundamental science
  - Perception of PEM electrolysis as “old” technology
  - Gap between scientific “solutions” and real world issues
- Lack of sufficient funds for thorough experimental study
  - Premature downselect may miss best options
- Lack of funding opportunities for system level R&D

Opportunities

- High potential for continuing advancements
  - Need to move demonstrated concepts to production
- Ability to leverage fuel cell R&D and supply chain
  - Small additional investments have high payoff
- Research tools and materials from other fields
- Ability to implement process automation and labor reductions for high volume cost savings

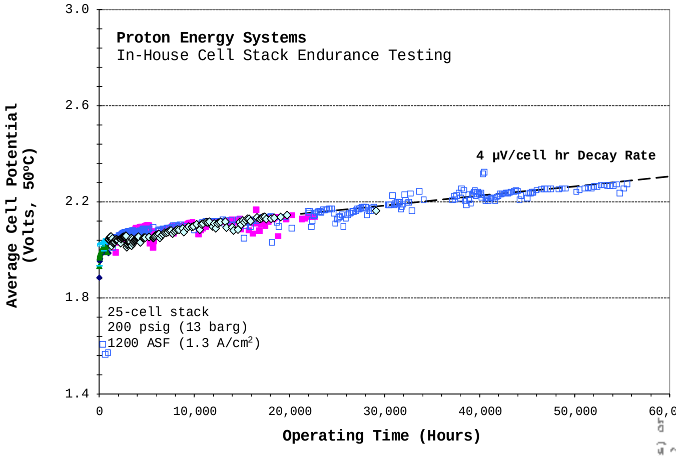
Recommendations

- Continue to communicate needs and discuss strategy with DOE and other agencies
  - PEM electrolysis stack and system roadmaps defined
- Commit to concerted and focused program in hydrogen production technologies
- Encourage university and lab collaborations
- Coordinate with DoD as early adopters
- Balance stack and system funding for critical advancements and commercial validation

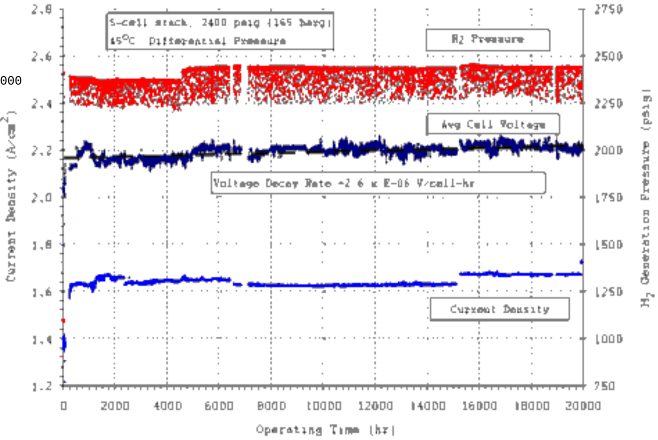
Back up slides

P. I./Presenter Name: Dr. Katherine Ayers
Organization: Proton OnSite
Date: May 11, 2012

Established PEM Stack Durability



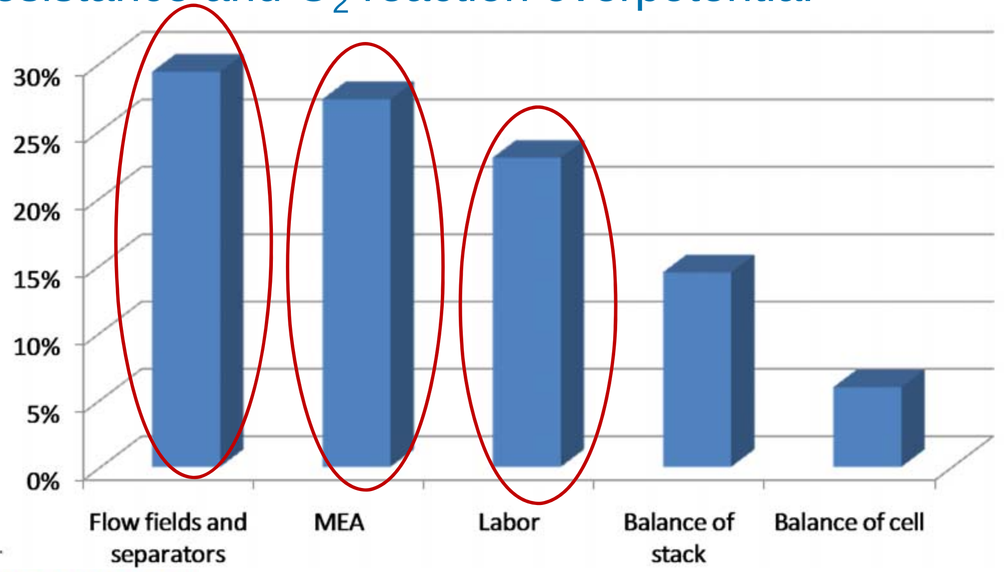
~60,000 hours of operation demonstrated in commercial stack



20,000 hours of operation demonstrated at 2400 psi

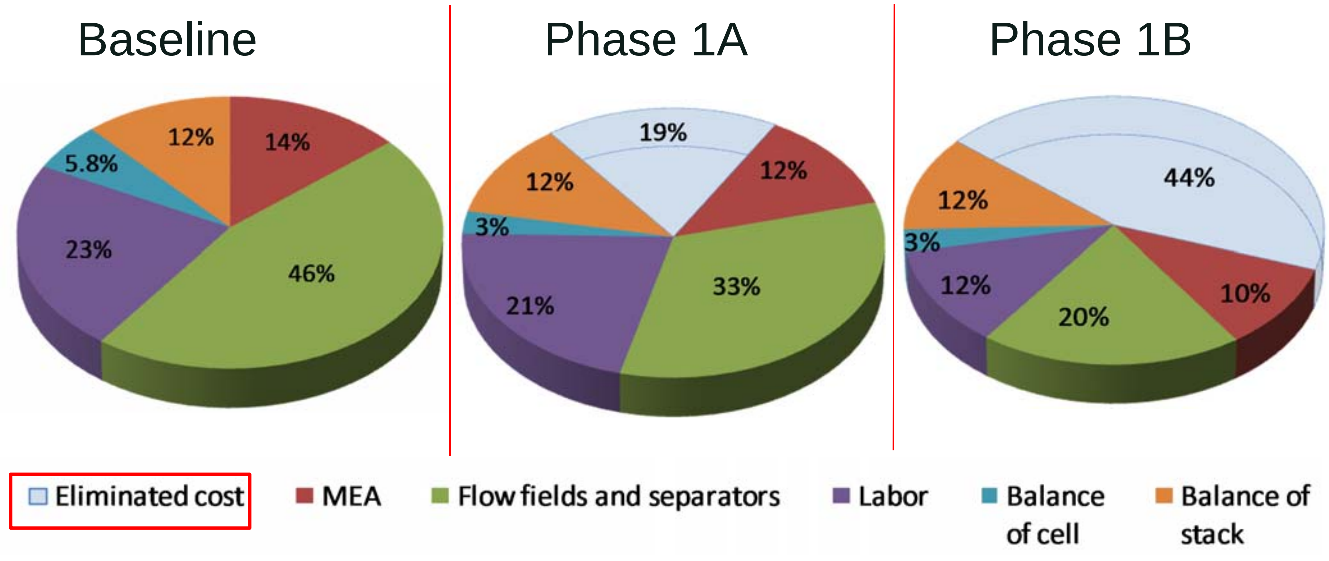
Current Cost and Efficiency Limitations

- Flow field, membrane electrode assembly, and labor are high impact cost areas
- Efficiency losses dominated by membrane ionic resistance and O_2 reaction overpotential

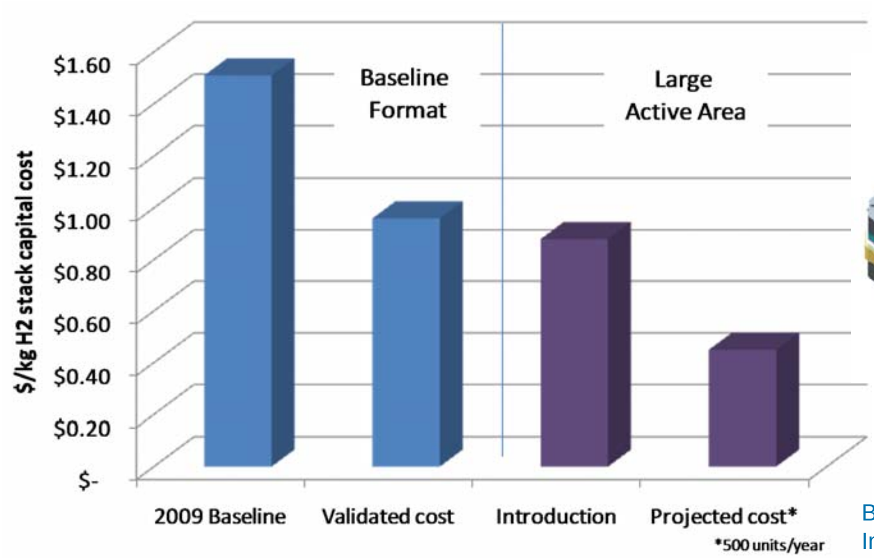


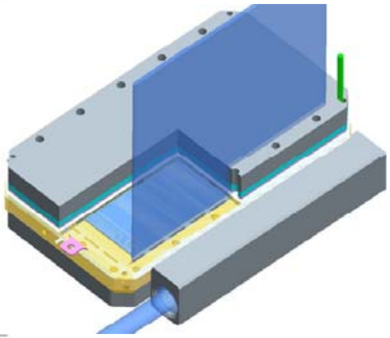
Near Term Cost Reduction

- Combined labor and material advancements result in 19% production cell stack cost reduction
- Project additional step change in Phase 2



Stack Scale Up/H2A Impact

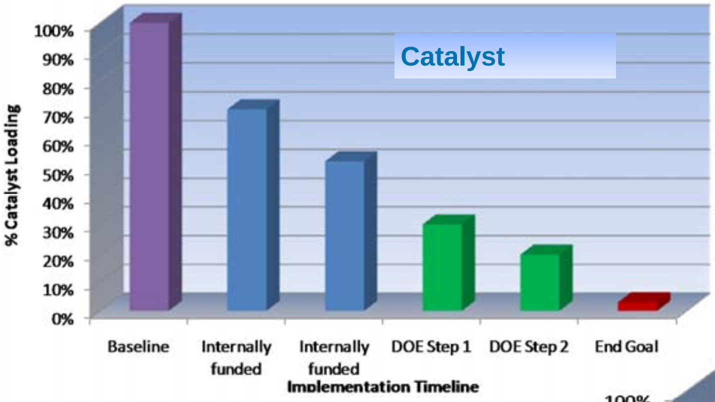


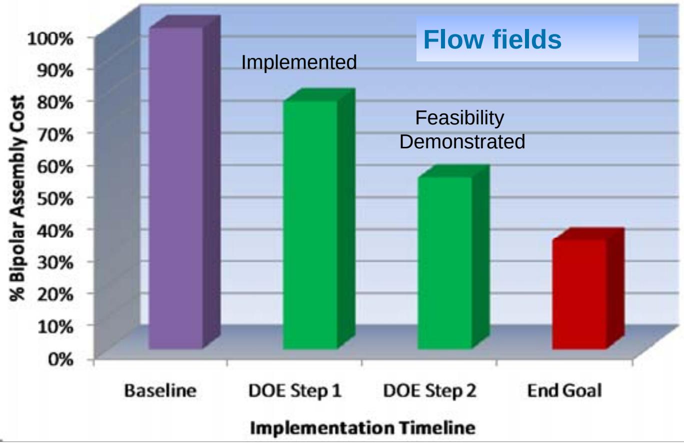


Based on H2A model V2.1,
Includes cost over system life

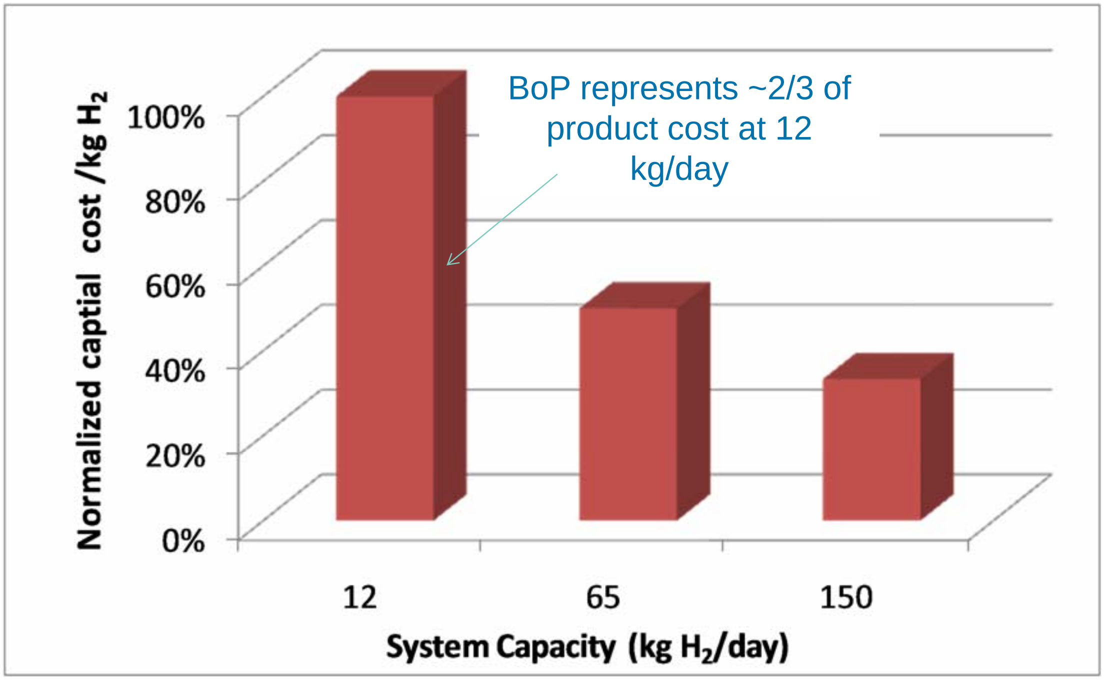
- Large active area stack:
  - Reduced labor vs. 2009 baseline stack cost
  - Stack designed for minimization of scrap for major materials
  - FEA and CFD modeling in progress

Long Term Material Cost Reduction





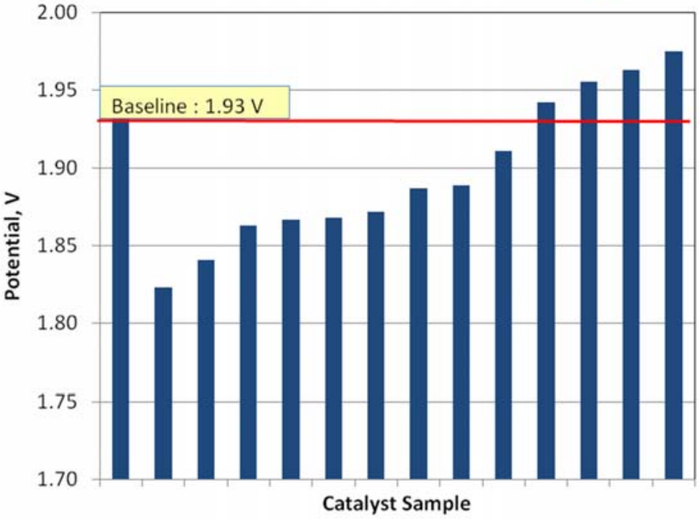
Impact of Scale Up on Balance of Plant Cost



BoP represents ~2/3 of product cost at 12 kg/day

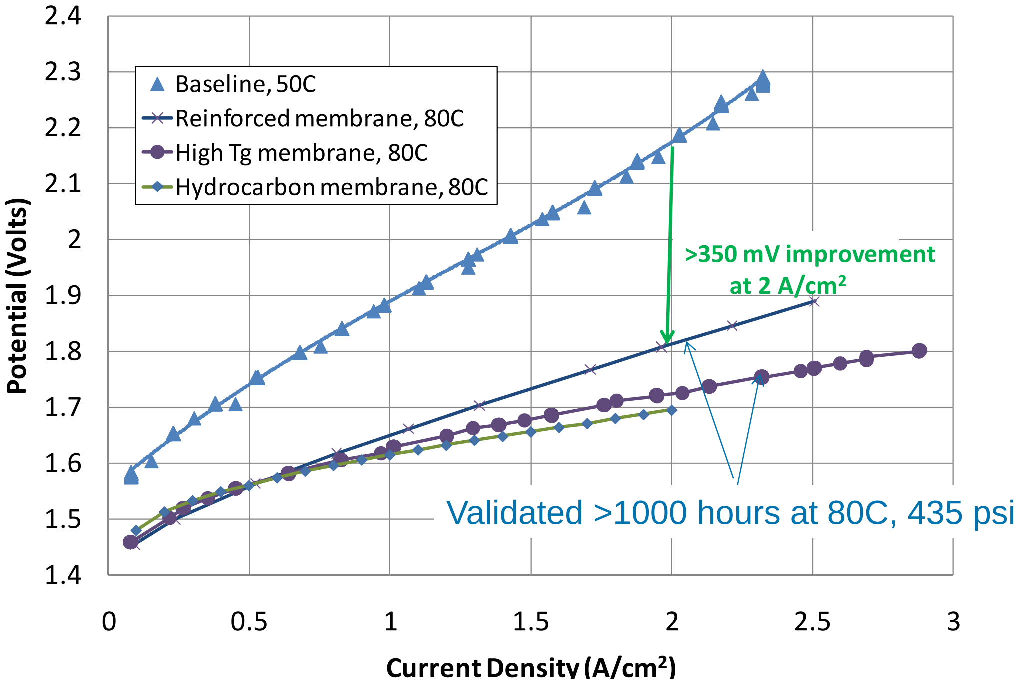
Catalyst Improvements

- Many samples improved vs. baseline
- Stability to 500 hours without voltage degradation



Membrane Improvements

- Multiple pathways showing promise



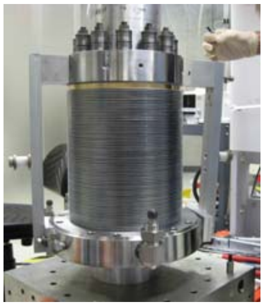
>350 mV improvement at 2 A/cm²

Validated >1000 hours at 80C, 435 psi

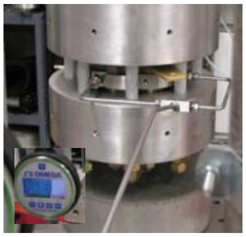
Development Successes, 2008-11

- Typical timeline of 12-18 months

65 kg/day system



0.23 ft² cell stack



5000 psi cell stack

10,000 psi fueler

DOE bipolar plate

0.6 ft² cell stack

CERL RFC 2400 psi System

Proton Fueling Station

- H_2 from electrolysis test area, >65 kg/day generation capacity, power supplemented with 75 kW solar
- 700 bar fast fill capable, 90 kg storage
- Qualified for Toyota, GM, and Daimler vehicles

More than 1000 H_2 fills / 3,000 kg / 150,000 miles to date

PROTON ON SITE

Path Forward for Widespread Production of Affordable Renewable Hydrogen for Future Energy Scenarios

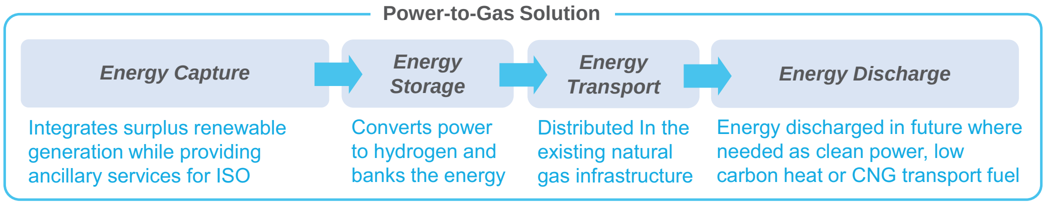
Large Scale Electrolytic Hydrogen

Joseph Cargnelli
jcargnelli@hydrogenics.com
Chief Technology Officer

May 10-12th, 2012
Workshop at Crystal City Gateway Marriott, Arlington, VA

Current Situation

- Energy storage is not a new requirement, but the scale of energy storage required with the increased penetration of renewables in the generation mix has changed—100's of MWh in any given hour
- There are different ways of tackling problem of utility-scale energy storage. How to choose? Demonstration projects…
- **Power-to-Gas** is a hybrid utility-scale energy storage solution which bridges the gas and electric systems
  - Uses existing natural gas infrastructure to bank energy and the existing power assets of third parties
  - Energy stored can be virtually discharged at any time and place on the power or gas system—power, heat or CNG fuel
- **Hydrogenics and Enbridge**, a leading gas distribution company, signed an agreement in April to jointly develop utility-scale Power-to-Gas projects in North America



Power-to-Gas Solution

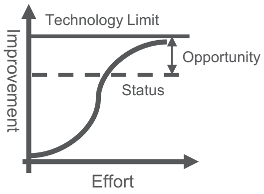
Energy Capture	*Energy Storage*	*Energy Transport*	*Energy Discharge*
Integrates surplus renewable generation while providing ancillary services for ISO	Converts power to hydrogen and banks the energy	Distributed In the existing natural gas infrastructure	Energy discharged in future where needed as clean power, low carbon heat or CNG transport fuel

Many commercialization challenges remain:

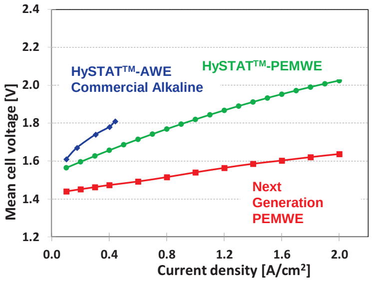
- ***Scaling PEM Electrolyzer capacity***
- ***Gas inter-operability codes and standards for injecting hydrogen into natural gas system in each jurisdiction; (Hawaii is a leading model)***
- ***Ability to monetize a sufficient portion of the system-wide benefits of Power-to-Gas to secure capital investments***

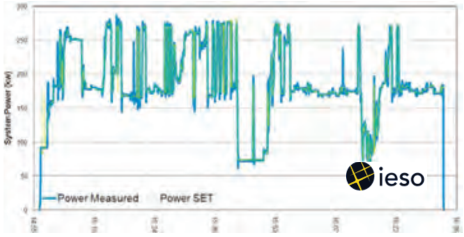
Electrolyzer Technology Status and Opportunities

Stack Parameter	2011 PEMWE	2013-2015 PEMWE	2011 AWE	2013-2015 AWE
Efficiency	73 – 93% HHV 62 – 79% LHV	90 – 99% HHV 77 – 86% LHV	82 – 92% HHV 69 – 78% LHV	85 – 95% HHV 72 – 81% LHV
Overload Capability	150% [3 A/cm^2]	500% [10 A/cm^2 has been demonstrated]	135% [0.6 A/cm^2]	225% [1 A/cm^2]
Durability	30,000 hr	50,000 hr	70,000 hr	70,000 hr
Production Capacity	65 kg/day	540 kg/day	130 kg/day	130 kg/day
Grid Cycling Capability	✓	✓	✓	✓
Price (normalized)	1.44	0.54	1.00	0.9
Cell Active Area	755 cm^2	1250 cm^2	4000 cm^2	4000 cm^2
Input Power	150 kW	1100 kW	400 kW	400 kW
Gas Delivery Pressure	10 bar	30 bar	10 – 25 bar	10 bar



How much improvement remains to be made?





HySTAT^{TM} AWE electrolyser provided frequency regulation by responding to real-time frequency regulation signals from the IESO on a second-by-second basis.

MW PEMWE Challenges

Technology Area	Driver	Importance	Understanding	Opportunity	Classification
Membrane	Reduce membrane thickness	9	High	High	High Priority Research
	Membrane mechanical reinforcement	5	Medium	Medium	High Priority Research
	Membrane edge protection	7	High	Medium	Engineering
	Improve membrane dimensional stability	9	High	High	High Priority Research
	Lower cost membrane material	5	Medium	Medium	Medium Priority Research
Catalyst	Catalyst loading reduction (O2)	5	Medium	Medium	Medium Priority Research
	Catalyst loading reduction (H2)	3	Medium	Medium	Medium Priority Research
	Non-precious metal catalyst	3	Low	Low	Mature Technology
GDL	Optimize GDL thickness & porosity	3	Low	Low	Mature Technology
	Improved GDL support to membrane	9	High	Low	Mature Technology
	GDL thickness tolerance	3	Medium	Low	Mature Technology
	Carbon GDL mechanical strength	3	Medium	Medium	Engineering
Bipolar Plate	Plate material compatibility	9	High	Low	Mature Technology
	Low cost large active area plate	5	High	Medium	Engineering
Protection Coating	Alternate lower cost coating materials	9	Medium	High	High Priority Research
	Existing coating cost reduction	7	High	Medium	Engineering
Cell Design	High precision seal manufacturing	9	High	High	Engineering
	Reduce pressure drop	3	High	Low	Low Priority Research
Commercialization					
Deployment/Field Trials	Policy barriers; Gas inter-operability codes and standards for H2 injection into natural gas system	9	Low	High	High Priority
	Contracting to ensure a sufficient portion of the system wide benefits can be monetized for the developer	9	Medium	High	High Priority
	10 MW plant design and optimization	7	High	Medium	High Priority

Opportunities

The Big Picture:

- The bridging of the electrical power and gas grids enables the integration of increased renewable energy generation
- There is an immediate need for utility-scale energy storage solutions – this will drive MW-scale electrolysis today *(not contingent on FC vehicle deployments tomorrow);* fast growth possible
- Hawaii is a perfect candidate for the first 10 MW demonstration plant (existing mixed gas network and significant RE penetration)
- Significant cost reductions possible with development of large scale PEMWE

The Plan:

- Leverage PEM fuel cell design
- Leverage PEM fuel cell supply chain
- Increase stack efficiency
- Scale up cell active area and stack size
- BOP Simplification
- 10 MW pilot plant demonstration

1 MW PEMWE development in progress.

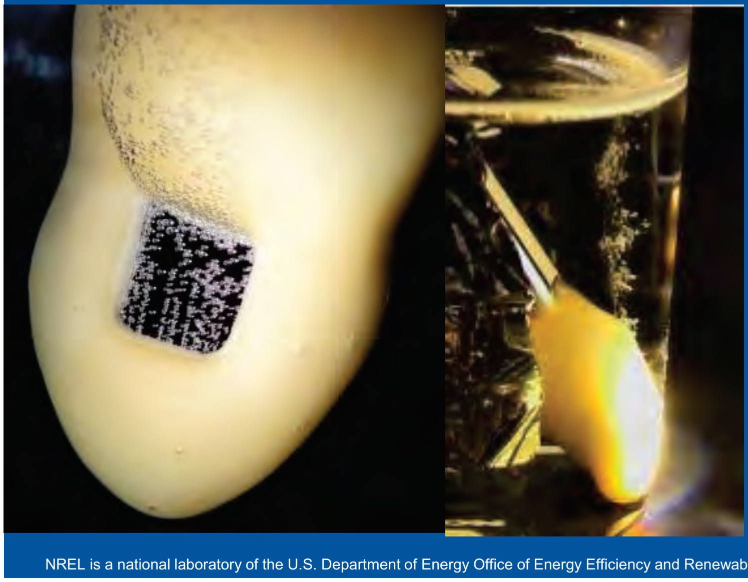
Key Points & Recommendations

- Hydrogenics and its partners are committed in the development and commercialization of Power-to-Gas
- Large scale PEMWE is entering a phase where engineering and manufacturing will become as important as technical leadership
- Cost and Efficiency targets will be achieved by leveraging of PEM fuel cell progress without requiring major new R & D investments. Focus should be on cost reduction, engineering scale-up, and market development.
- Hydrogenics is developing a MW PEMWE stack building block. MW-scale PEMWE will offer a major step toward affordable large-scale renewable hydrogen
- Government-Industry investment required to demonstrate cost and efficiency of a 10 MW Demonstration Plant. These results will be used to refine the design and cost estimates for a centralized hydrogen plant (>50,000 kg/day).

Are we not better off channeling some of the money going into CAES and batteries into the design, development , construction and operation of North America's first Power-to-Gas 10 MW demonstration facility?

NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Hydrogen Production from Photoelectrochemical Systems



Hydrogen Production Expert Panel Workshop

John A. Turner
jturner@nrel.gov

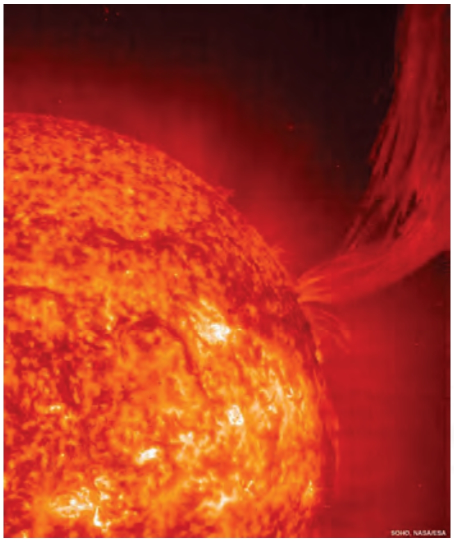
May 10, 2012

NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Direct Conversion Systems

Visible light has sufficient energy to split water (H_2O) into **Hydrogen and Oxygen**

Requires the combination of a Light Harvesting System and a Water Splitting System

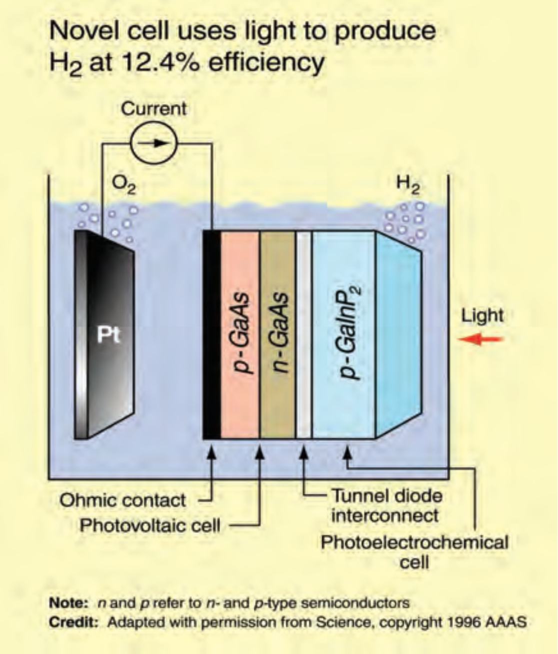


- ✓ Semiconductor photoelectrolysis
- ✓ Photobiological Systems
- ✓ Homogeneous water splitting
- ✓ Heterogeneous water splitting

(Sunlight and Water to Hydrogen with No External Electron Flow)

Status:High Efficiency Photoelectrolysis Device

Science, April 17 1998


Novel cell uses light to produce H_2 at 12.4% efficiency

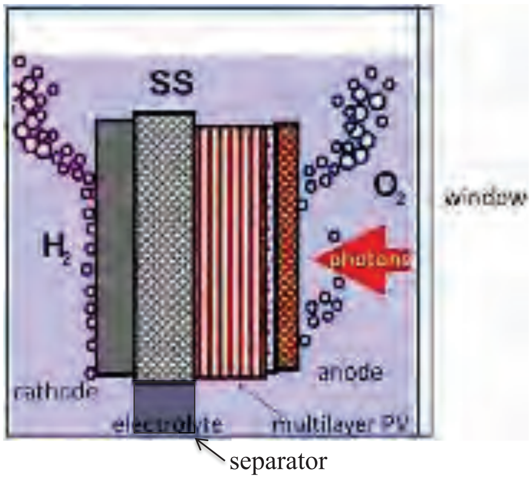
Note: *n* and *p* refer to *n*- and *p*-type semiconductors
Credit: Adapted with permission from Science, copyright 1996 AAAS

- Direct water electrolysis
- Tandem (PV/PEC) design
- **12.4% Solar-to-hydrogen**
- Corrosion limited lifetime

Experimental Cell

Challenges: Photoelectrochemical (PEC) Systems

Generic PEC Device



Eric Miller

Ideal Characteristics:

- ☐ **Photoabsorber**
  - ☐ High photoconversion efficiency
  - ☐ Proper energetics
- ☐ **Catalysis**
  - ☐ Efficient, selective catalysts with low losses
  - ☐ Charges well-coupled to catalytic reactions
- ☐ **Stability under photolysis**
  - ☐ Semiconductor
  - ☐ Catalyst/electrolyte interface

Fundamental and exploratory science to address these challenges for commercializable PEC systems for hydrogen

Challenges: Technoeconomic Analysis of the costs for PEC Hydrogen

PEC systems have an innovative approach and offer significant cost reductions for solar hydrogen production.

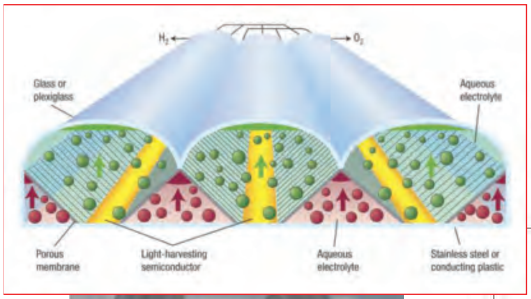
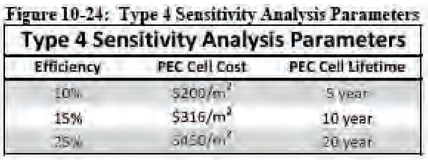


Figure 10-24: Type 4 Sensitivity Analysis Parameters



Type 4 Sensitivity Analysis Parameters		
Efficiency	PEC Cell Cost	PEC Cell Lifetime
10%	$200/m^2	5 year
15%	$316/m^2	10 year
25%	$450/m^2	20 year

Tracking concentrator system

Figure 10-25: Overall Type 4 Cost Sensitivities ($/kgH$_2$)

B.D. James, G.N. Baum, J. Perez, K.N. Baum, “Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production”, DOE Report (2009) http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pec_technoeconomic_analysis.pdf

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Opportunity: Discovering New PEC Semiconductors

Utilize advanced theory to provide direction and focus the effort.

Band structure calculations using Density Functional Theory can give you spectra, nature of the transition (direct, indirect), lattice constants and band gap energy trends.

The actual band structure depends on

Symmetry, composition, bond length

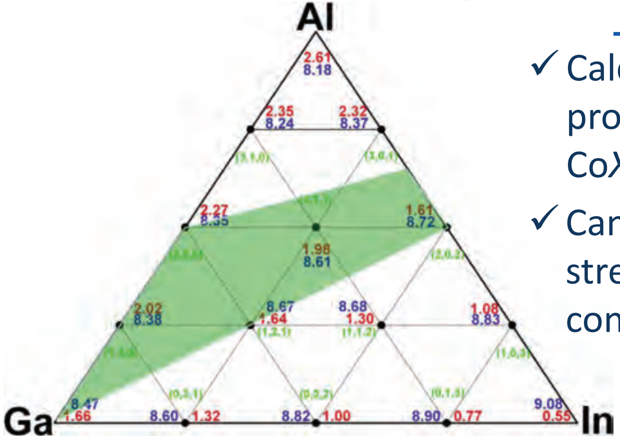
and requires

Sophisticated DFT calculations

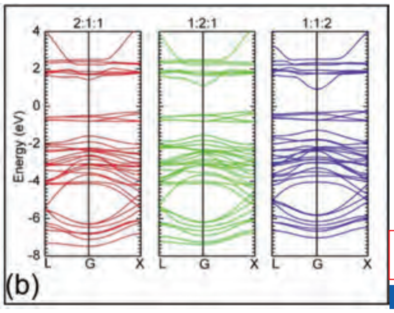
A collaboration of theory, synthesis, and characterization groups along with mathematicians is necessary to achieve fundamental PEC goals.

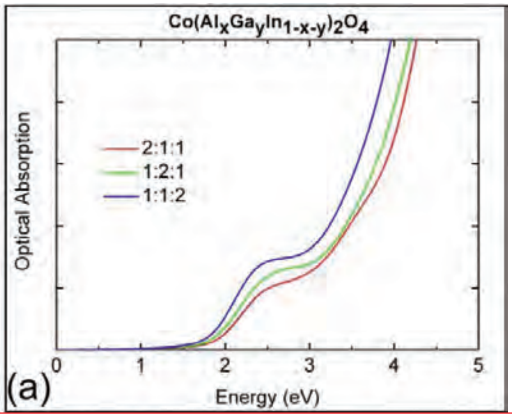
Opportunity: mixed metal oxides

- ✓ Calculated electronic and optical properties of Co based spinel oxide CoX_2O_4 (X=Al, Ga, In) with DFT
- ✓ Can tune band gap, absorption strength, carrier effective masses by controlling alloy composition



Calculated band gap, lattice constant as a function of Al:Ga:In. Shaded area best for PEC





Appl. Phys. Lett. 100, 023901 (2012)

Conclusions/Recommendations

PEC Material Criteria

- A band gap in the range 1.7eV <Eg< 2.2eV
- High carrier mobility, low resistivity
- High quantum yield (>80%)
- Controlled p-,n- doping
- Low-cost and high-volume synthesis
- Stable in an aqueous electrolyte
- Band edge positions for driving redox half-reactions

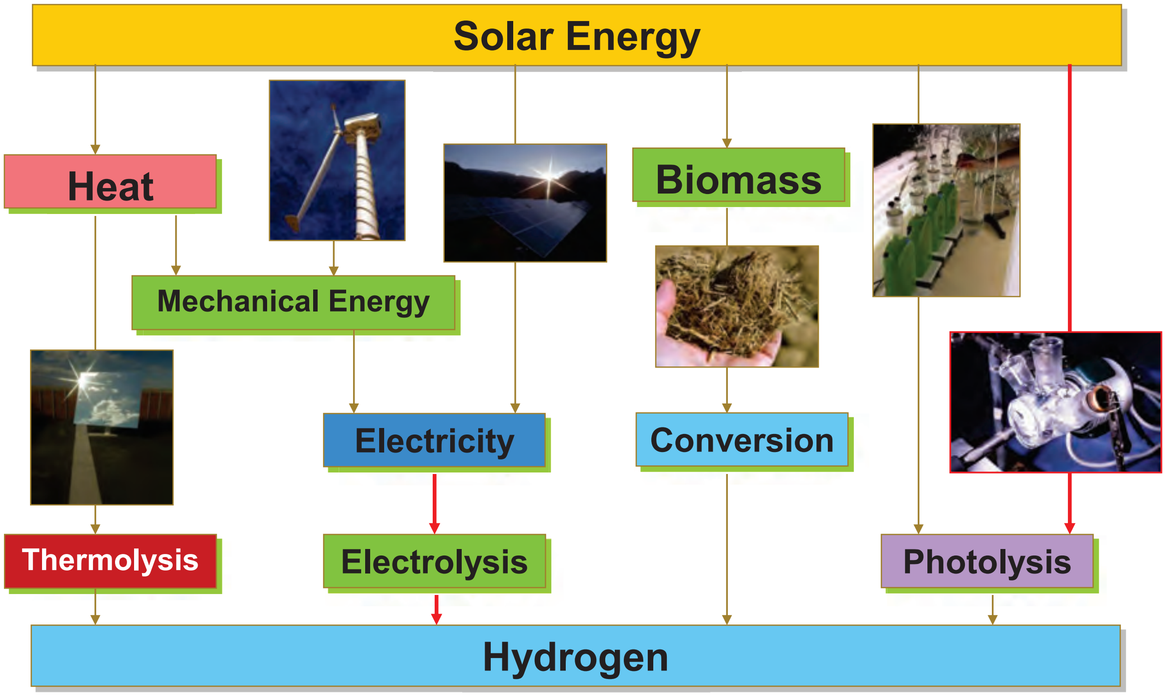
A search for PEC materials is fundamentally a search for PV materials

Path Forward

- ✓ Photoelectrochemical water splitting needs new materials, our first silicon.
- ✓ This material may or may not be useful for PV, but still must have the same solid-state internal efficiency as commercial PV devices.
- ✓ A collaboration of theory, synthesis, and characterization groups is necessary to achieve fundamental PEC goals.
- ✓ Once you have a good semiconducting (PV) material, catalysis is everything

SUPPLEMENTAL

Sustainable Paths to Hydrogen



Solar Energy

Heat

Biomass

Mechanical Energy

Electricity

Conversion

Thermolysis

Electrolysis

Photolysis

Hydrogen

Historical Perspective/Objectives

“Holy Grails of Chemistry”, *Accounts of Chemical Research,* vol 28 (1995)

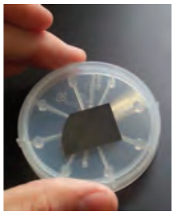
Allen J. Bard & Marye Anne Fox “Artificial Photosynthesis: Solar Splitting of Water to Hydrogen and Oxygen”

Water splitting “Holy Grail” definition: “We want an efficient and long-lived system for splitting water to H_2 andO_2 with light in the terrestrial (AM1.5) solar spectrum at an intensity of one sun. For a practical system, an energy efficiency of at least 10% appears to be necessary. This means that the H_2 and O_2 produced in the system have a fuel value of at least 10% of the solar energy incident on the system….and will not be consumed or degraded under irradiation for at least 10 years.”

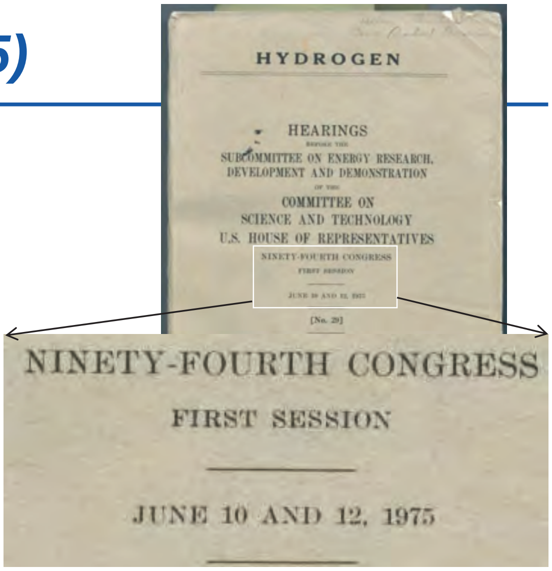
PEC material criteria includes PV material

- A band gap in the range 1.7eV <Eg< 2.2eV
- High carrier mobility, low resistivity
- High quantum yield (>80%)
- Controlled p-,n- doping
- Low-cost and high-volume synthesis
- Stable in an aqueous electrolyte
- Band edge positions for driving redox half-reactions

A search for PEC materials is fundamentally a search for PV materials



Hydrogen Economy *(1975)*



HYDROGEN

HEARINGS
BEFORE THE
SUBCOMMITTEE ON ENERGY RESEARCH,
DEVELOPMENT AND DEMONSTRATION
OF THE
COMMITTEE ON
SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES
NINETY-FOURTH CONGRESS
FIRST SESSION

JUNE 10 AND 12, 1975

[No. 29]

Conclusions

- Hydrogen is clean burning, the main combustion product is clean water.
- It may be substituted for nearly all fuel uses.
- It can be produced from domestic resources.
- It is available from a renewable and universal resource—water.
- Nearly all primary energy sources, nuclear, solar, etc. can be used in its production.

"In the long term the panel envisions an energy economy based on nonfossil sources, with electricity and hydrogen being the staple forms of energy distributed to cities and industries. *The transition from fossil fuels to synthetic fuels will occur when the total cost of producing and using fuels from nonfossil energy sources intersects the rising costs, including environmental effects, of coal and imported oil and gas*."

Pathways to Renewable Hydrogen

Tom Jarvi

Sun Catalytix

Renewable Hydrogen

Conventional pathways to renewable hydrogen establish economic benchmark

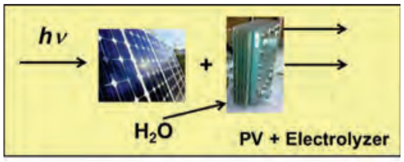
Renewable power

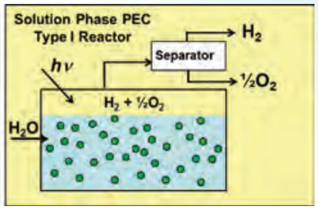
+

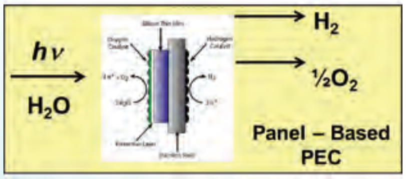
Electrolysis

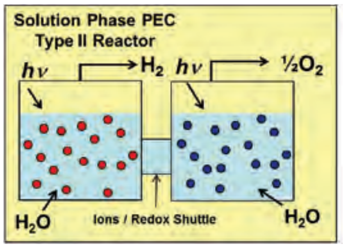
Solar Hydrogen

Several ways exist to generate solar hydrogen







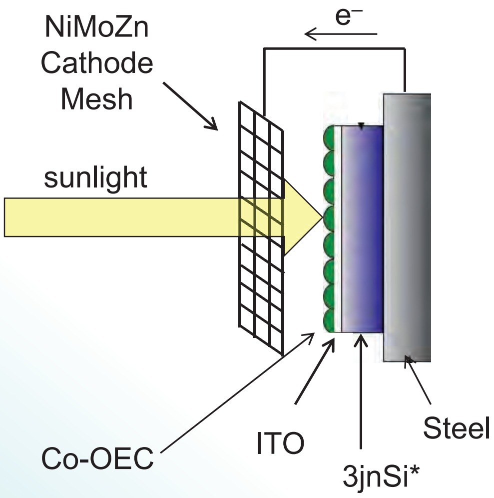


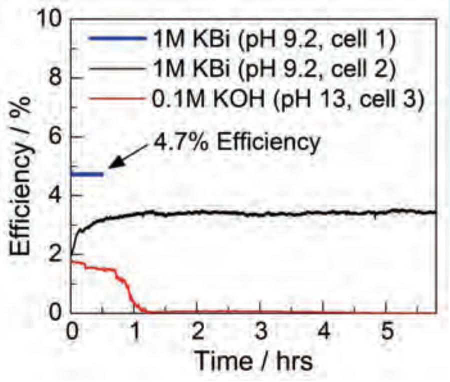
Conventional light collection dominates cost

Low cost light absorbing materials offer low-cost potential

Sun Catalytix

Example Result: Panel-Based PEC Performance





4.7 % Efficiency achieved with the best solar cell samples (~8% PV efficiency). Observed improved stability in borate electrolyte vs. KOH.

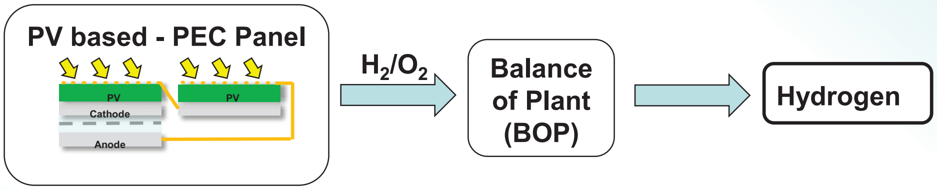
**triple-junction cells provided by Xunlight/Midwest Optoelectronics*

Steven Y. Reece *et. al.*, *Science* **334** (2011) 645.

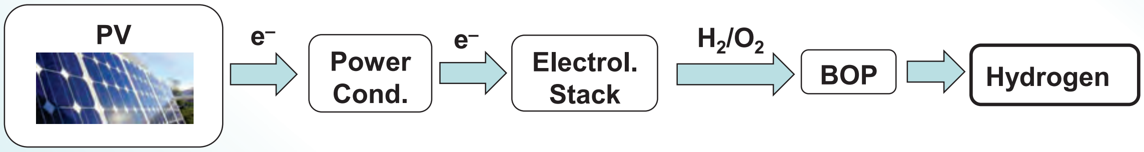
Sun Catalytix

Challenge: Cost of Hydrogen from PEC, PV + Electrolyzer

Panel PEC



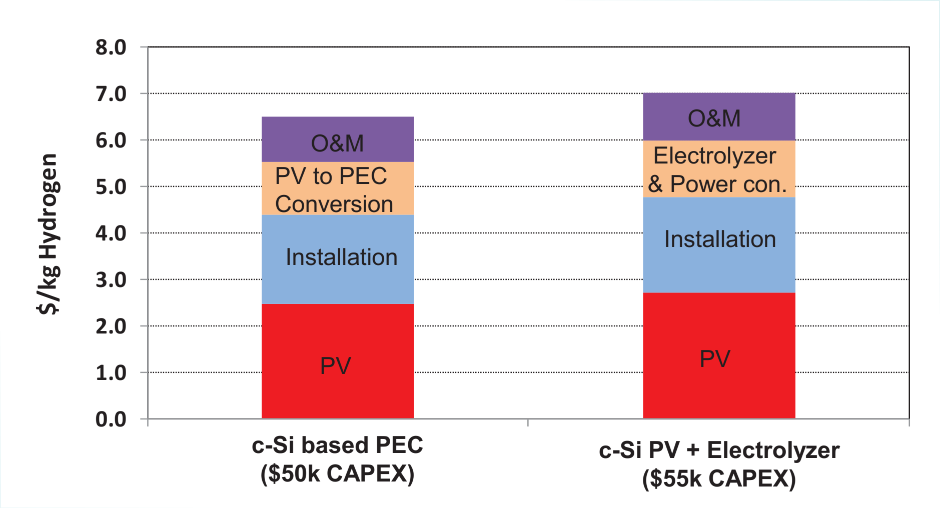
PV + Electrolyzer



Notes:

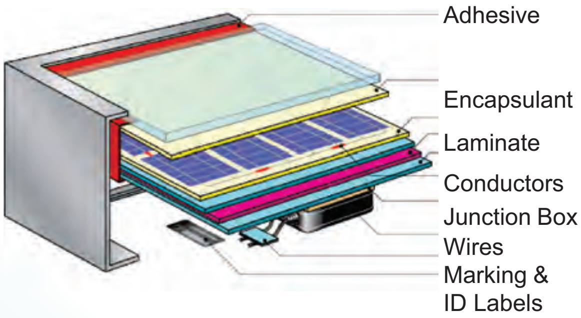
- *Output was 2 kg/day hydrogen in each case*
- *Hydrogen produced at low pressure (<100 psi) in both cases*
- *PV performance is maximized at all light levels by the power conditioning*

Challenge: PEC Comparable to PV Plus Electrolyzer



- *Installation and PV module costs dominate and are comparable for the PV + electrolyzer and PEC cases*
- *Difference between PV + electrolyzer and PEC is invariant to PV material.*
- *O&M calculated for a 20-yr life – is this viable for PEC?*

Opportunities for Low-Cost Light Harvesting Systems



Source: www.hiscoinc.com

Silicon photo-voltaics are engineered to protect high-cost light absorber.

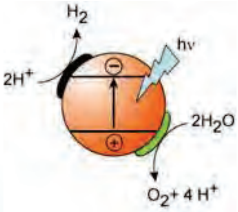
Algae bioreactors are engineered for simplicity to drive down costs.

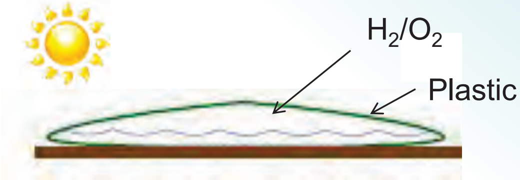
Credit: Seambiotic

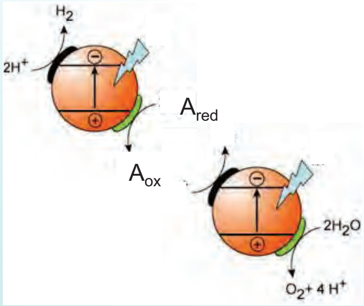
Opportunities for Low-Cost Light Harvesting Materials

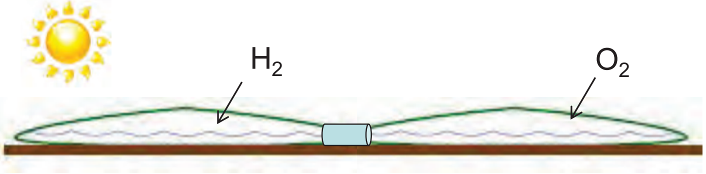
Low-cost Particulate Photocatalysts

Simple, Low-Cost Plastic Containers

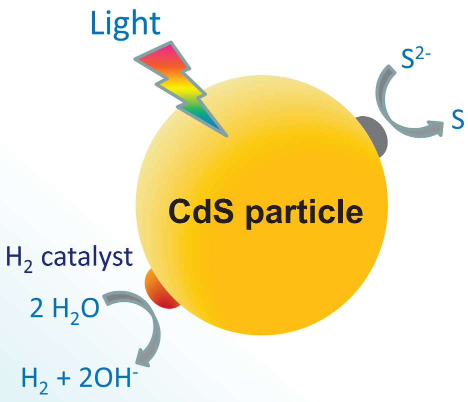


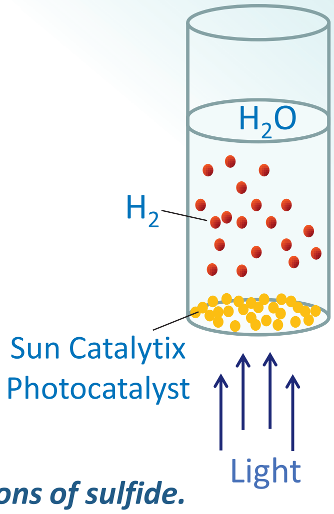






Example of Particle-Based Photocatalysis





- *Light can be used to generate hydrogen from solutions of sulfide.*
- *Current research efforts aimed towards generation of hydrogen and oxygen.*

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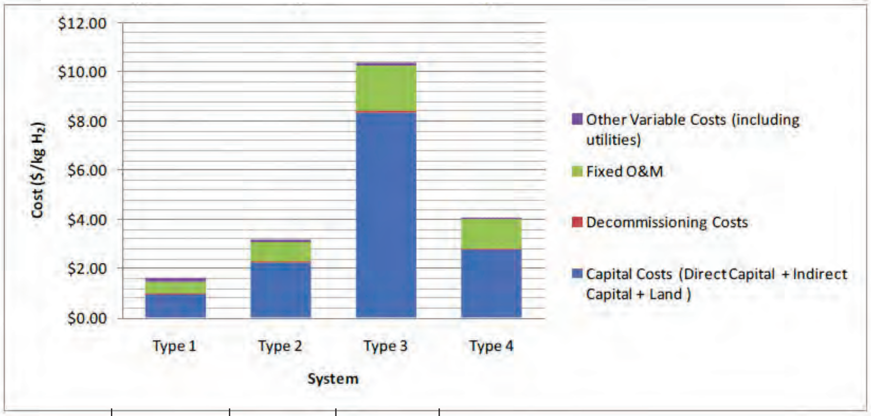
Hydrogen Cost by Different PEC Approaches



Light absorber	Particles	Particles	Panel	Panel & Concentrator
Reactor Gas Output	Mixed H_2/O_2	H_2	H_2	H_2

Notes:
(1) H_2 production: 10 metric ton per day with ten 1 ton/day units
(2) Costs include estimates for separation

DOE-funded analysis suggests particle based systems offer lowest cost

B. D. James, G. N. Baum, J. Perez, K. N. Baum, U.S. Department of Energy, Dec. 2009.
Available online at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/pec_technoeconomic_analysis.pdf.

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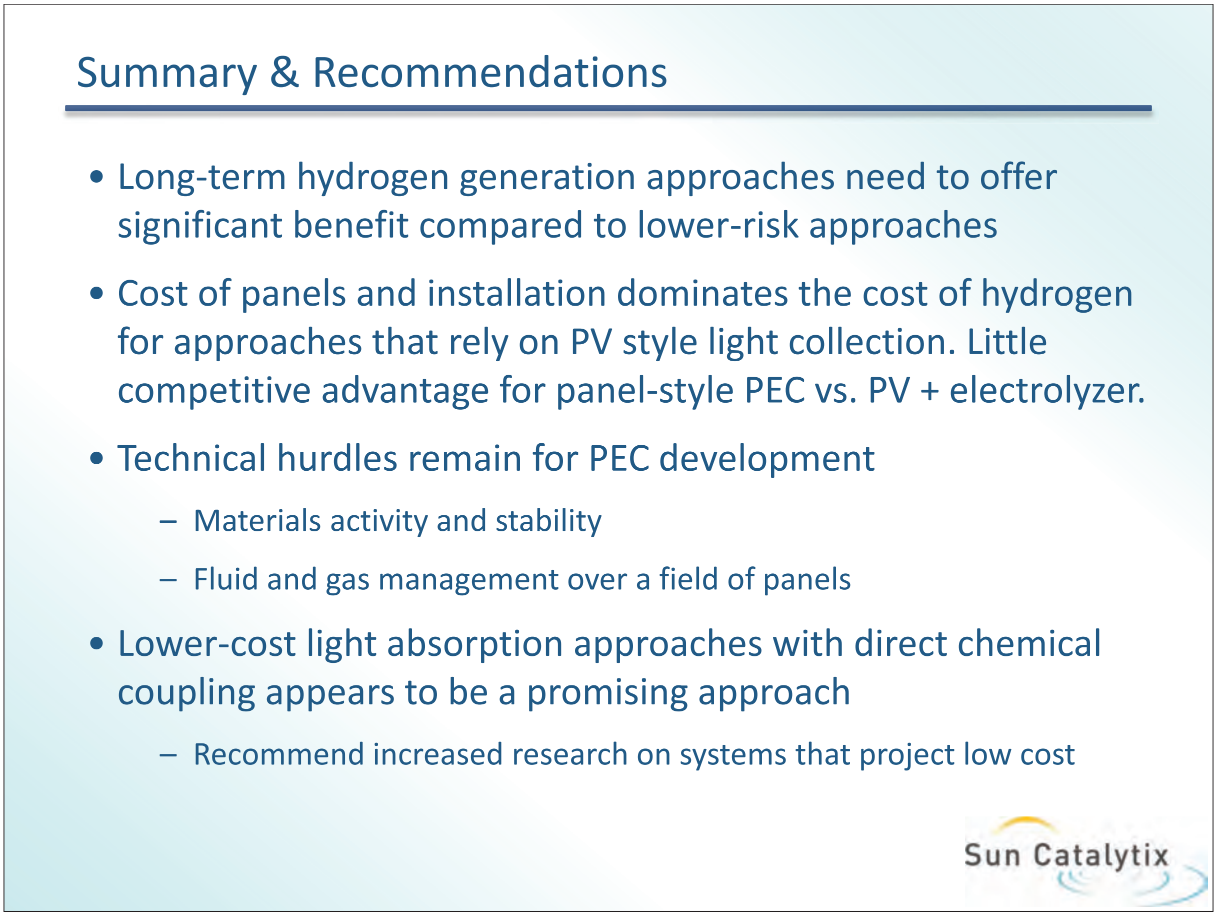


Summary & Recommendations

- Long-term hydrogen generation approaches need to offer significant benefit compared to lower-risk approaches
- Cost of panels and installation dominates the cost of hydrogen for approaches that rely on PV style light collection. Little competitive advantage for panel-style PEC vs. PV + electrolyzer.
- Technical hurdles remain for PEC development
  - Materials activity and stability
  - Fluid and gas management over a field of panels
- Lower-cost light absorption approaches with direct chemical coupling appears to be a promising approach
  - Recommend increased research on systems that project low cost

Sun Catalytix

Microbial Electrochemical Technologies and Osmotic Power for Bioelectrochemical H_2 Gas Production

Bruce E. Logan
Penn State University

- New paradigm for H_2 Production:

  Run a Hydrogen Economy (transportation) using water
- There are vast resources of untapped energy/ power sources within our communities and industries that we currently do not use
  - Wastewater, cellulosic biomass, freshwater, heat

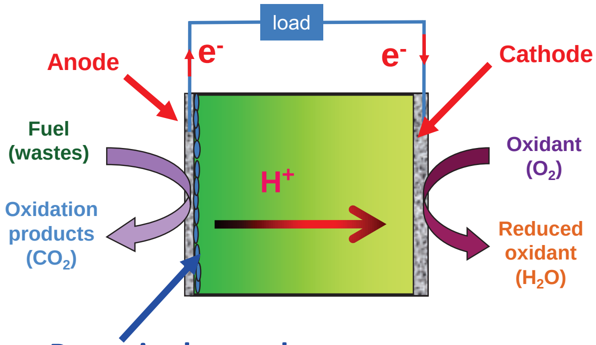
New Energy Sources Based on METs

- Energy use in the USA
  - 3.3 TW total; 500 GW electricity produced
- Wastewater organic matter (WW)
  - Consume 15 GW for our water infrastructure (5%)
  - Could produce **17 GW** from WW (Savings 3x15 + 17 = 62 GW net)
- Cellulose Biomass Energy
  - **600 GW** available (based on 1.34 billion tons/yr of lignocellulose)
- Salinity Gradient Energy- Natural Waters (global values)
  - **980 GW** (from the 1900 GW available from river/ocean water)
  - **20 GW** available where WW flows into the ocean
- Waste Heat Energy
  - 200 – **500 TW**, industrial waste heat
  - **1000 GW,** power production (33% efficient power plants)

  (Does not include solar and geothermal energy sources)

Logan and Rabaey (submitted, *Science*; invited)
Logan and Elimelech (submitted, *Nature*; invited)

Electrical power generation in a microbial fuel cell (MFC) using exoelectrogenic microorganisms


load

Anode

e^-

e^-

Cathode

Fuel (wastes)

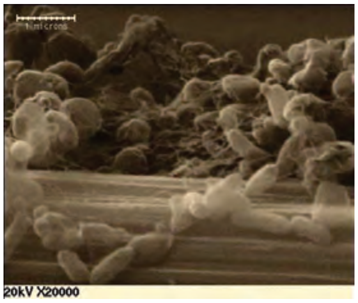
Oxidation products (CO_2)

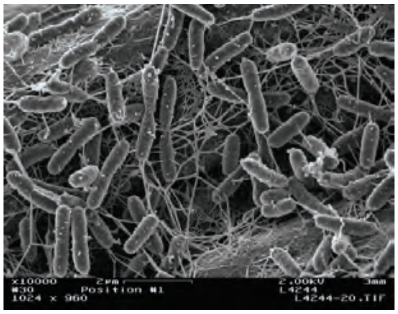
H^+

Oxidant (O_2)

Reduced oxidant (H_2O)

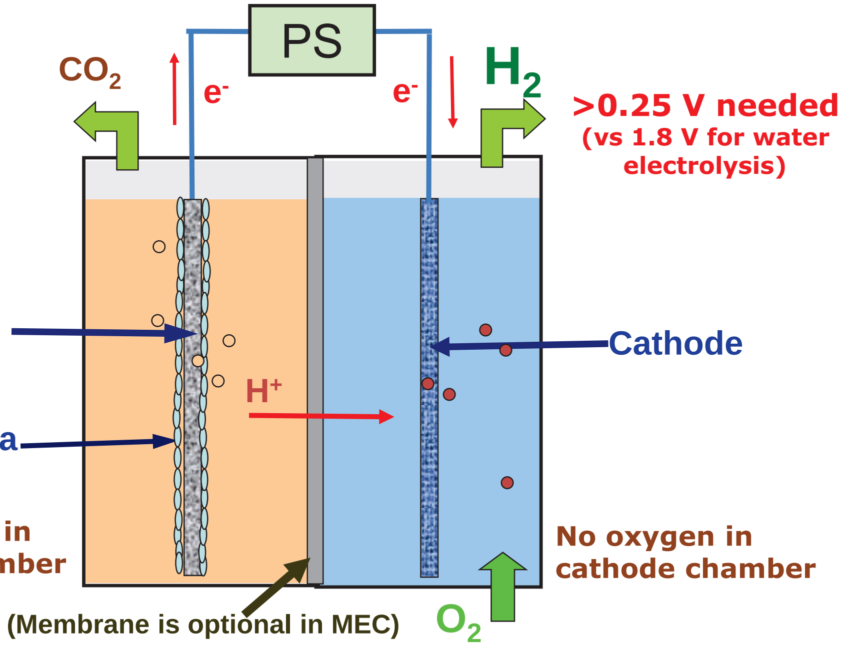
Bacteria that make electrical current





Liu et al. (2004) *Environ. Sci. Technol.*

Bioelectrochemical H_2 Production Using Microbial Electrolysis Cells (MECs)


PS

CO_2

e^-

e^-

H_2

>0.25 V needed
(vs 1.8 V for water electrolysis)

Anode

Cathode

H^+

Bacteria

No oxygen in anode chamber

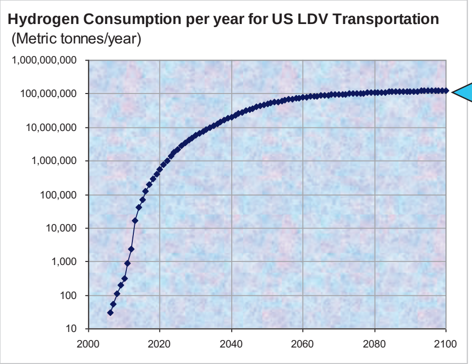
No oxygen in cathode chamber

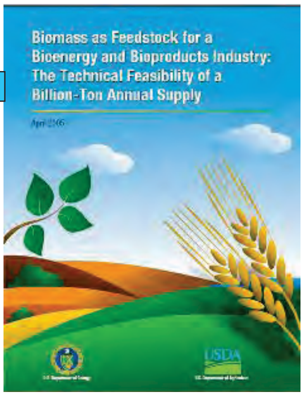
(Membrane is optional in MEC)

O_2

Liu, Grot and Logan (2005) *Environ. Sci. Technol.*

Cellulosic biomass → $\boxed{H_2}$



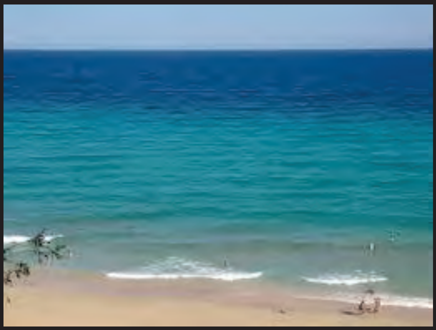

Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply

April 2005

Need 10^{11} kg/yr H_2 for transportation
(light duty vehicles)

1.34 billion tons of cellulose/yr
= 2×10^{11} kg/yr H_2
(meets 2060 final goal)

Salinity Gradient Energy



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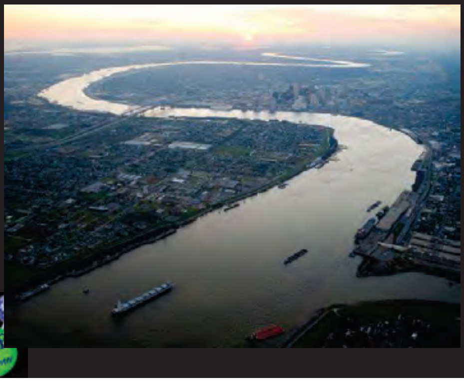

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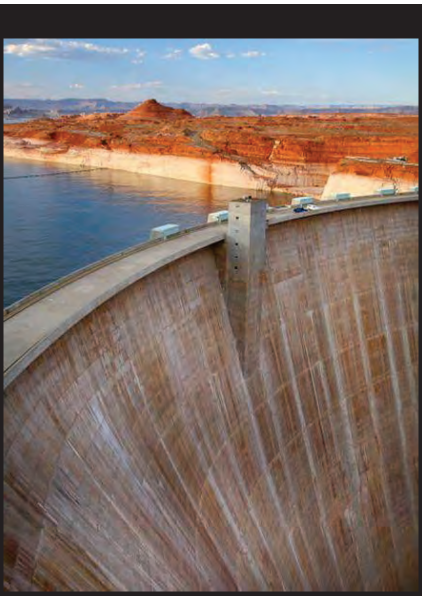
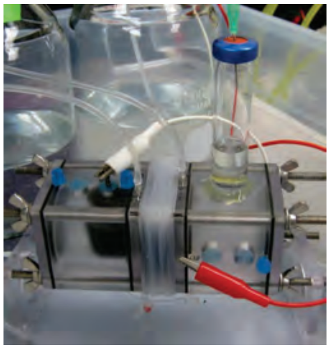
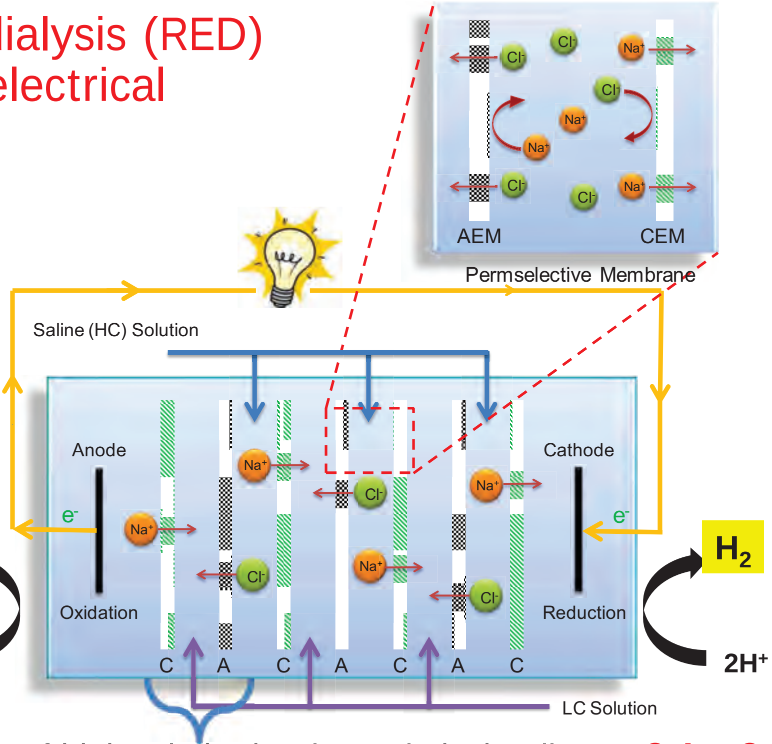


270 m of
Hydraulic Head

Oceanside WWTPs and Rivers could produce 980 GW

Reverse electrodialysis (RED) stack produces electrical current & H_2



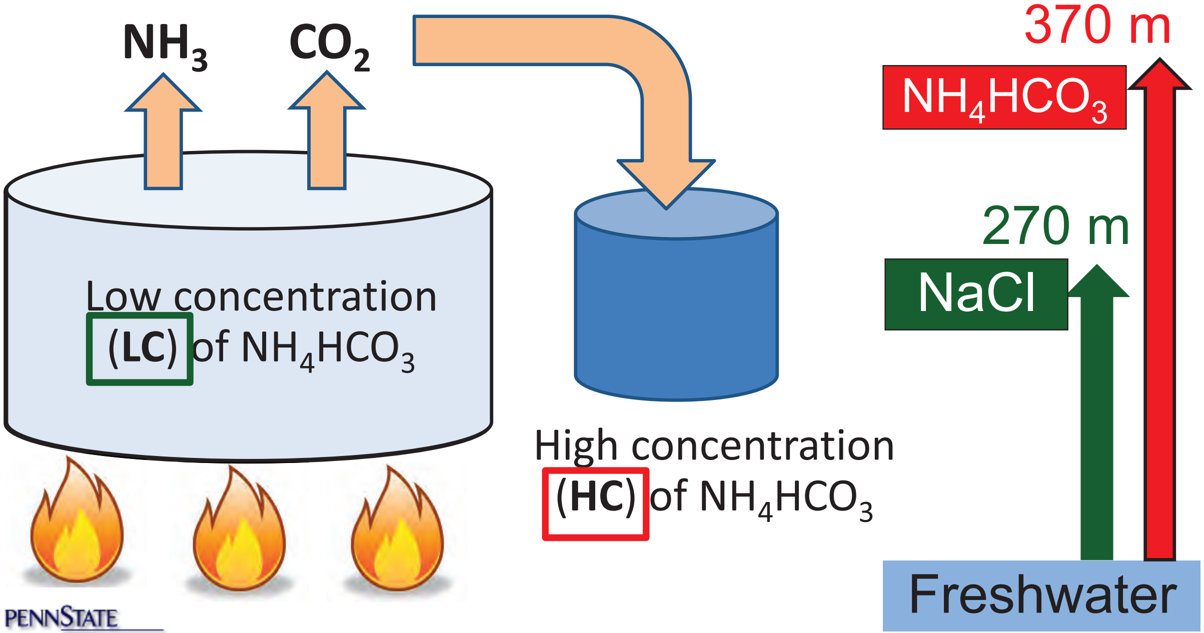


Each pair of high salt (HC) + low salt (LC) cells = **~0.1 – 0.2 V**

Logan and Elimelech (submitted)

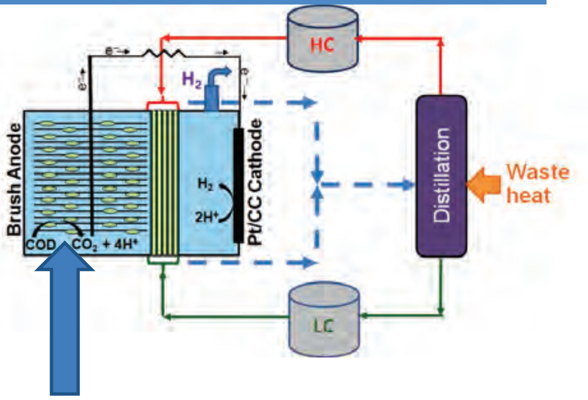
Capturing waste heat as energy

Ammonium Bicarbonate (**NH_4HCO_3**)



Cusick, Kim & Logan (2012) *Science*

RED Stack (abiotic) with NH_4HCO_3



- Abiotic anode
- Water splitting
- Many membranes

- Biotic anode (wastewater or biomass)
- No water splitting
- Few membranes

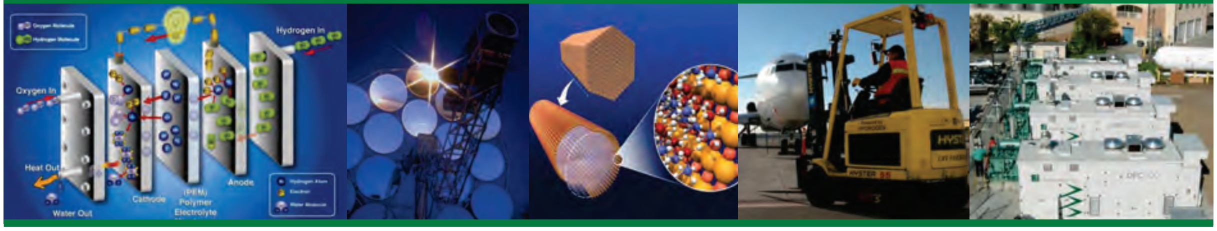
CONCLUSIONS

- Energy for H_2 production can be obtained from many new sources: biomass, wastewater, and salinity gradients (seawater-freshwater, and heat)
- Energy efficiencies can be very high

System	Energy Recovery	Energy Efficiency
MRFC– NaCl → Electricity	10%	42%
MRFC– AmB → Electricity	30%	34%
MREC– NaCl→ H_2	36%	65%
MREC – AmB → H_2	18%	35%

Challenges & Opportunities

- Challenges: Big picture
  - Renewable H_2 production needs to be emphasized
  - Better recognition/funding needed for NEW types of renewable H_2 production with near-term impact (microbial electrolysis cells “fall between the cracks” program)
- Challenges-Technical: Bio/osmotic/heat systems
  - Reactions at electrodes/materials/kinetics need to be improved (but with no or minimal precious metals)
  - Cost of membranes is a key factor in overall economics (new materials needed)
  - Full energy/feasibility analysis needed for MRCs
  - Europe is leading in osmotic energy systems development (we are behind)
- Opportunities
  - Advances in PEM systems will help MRC abiotic electrode system design, fabrication and implementation.
  - Incentives for “green” H_2 production could speed applications.



Solar Thermochemical

A.W. Weimer, University of Colorado

Workshop at Crystal City Gateway Marriott, Arlington VA
May 10-12, 2012

Technology Status/Challenges

- > 350 unique cycles have been discovered and scored
- 4 of those 12 are currently under active study by SHGR

Volatile Metal Oxides
•Zinc oxide
•Hybrid Cadmium
•Cadmium Carbonate
Challenge-avoiding recombination

Non-volatile Metal Oxides
•Iron oxide
•Sodium manganese
•Nickel manganese ferrite
•Zinc manganese ferrite
•M-ferrite
•M-ferrite/alumina ("hercynite") (2 steps)
•Ceria (2 steps)
Challenges-active materials robustness, scalable & efficient solar thermochemical redox reactor

Focus is Simple Two-step Non-volatile Metal Oxide Redox

Other
•Hybrid copper chloride (4 steps)
•Hybrid sulfur ammonia (5 steps)
Challenges-numerous unit operations, corrosive fluids, solids separation between steps; require electrolysis

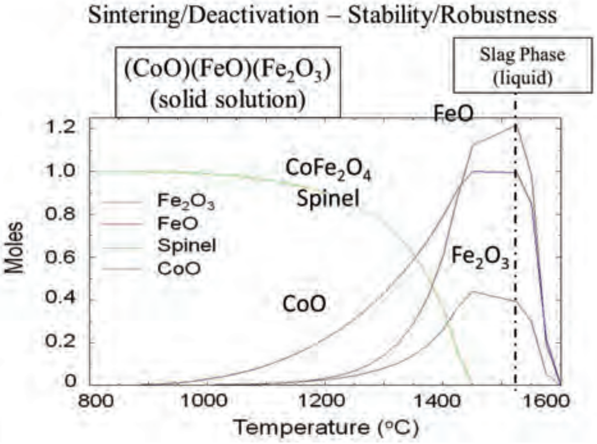
Metal Sulfates
•Cadmium sulfate
•Barium-Molybdenum sulfate
•Manganese sulfate
Challenge-side reactions more favorable

Sulfuric Acid
•Hybrid sulfur
•Sulfur iodine
•Multivalent sulfur
Challenge-requires 900^{o}C integrated solar/chemical plant

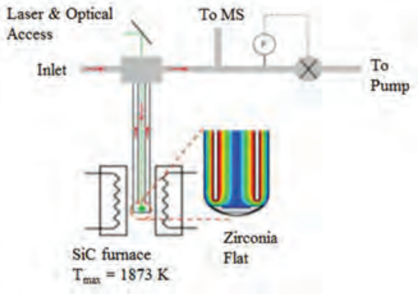
Materials Challenges

- Basic considerations.
  - Chemical composition
  - Macroscopic structure
    - Thermal Transport/Sunlight penetration
    - Gas transport
  - Microstructure
    - Reactive surface area
    - Thin active films to limit diffusional resistances
  - Structural stability and loading
- Understand complex behavior.
  - Surface/bulk reaction
  - Solid phase transport
    - Ionic species
  - Effects of dopants and supports
    - Reactivity/compatibility

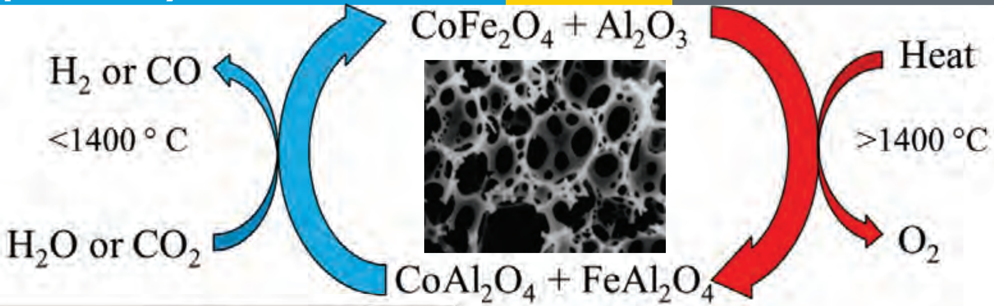
property	ferrite (Fe_2O_3)	ceria (CeO_2)	hercynite ($FeAl_2O_4$)	perovskite (ABO_3)	ideal
redox kinetics	SLOW	FAST	SLOW/MED	?	FAST
redox capacity	HIGH	LOW	HIGH	HIGH	HIGH
reduction T_H	MED/HIGH	HIGH	MEDIUM	LOW	LOW
durability	MEDIUM	HIGH	HIGH	?	HIGH
earth abundance	HIGH	LOW/MED	HIGH	?	HIGH


Sintering/Deactivation – Stability/Robustness

Problematic Ferrite Robustness



Nano-engineered Materials Opportunity



$CoFe_2O_4 + Al_2O_3$

H_2 or CO

<1400 ° C

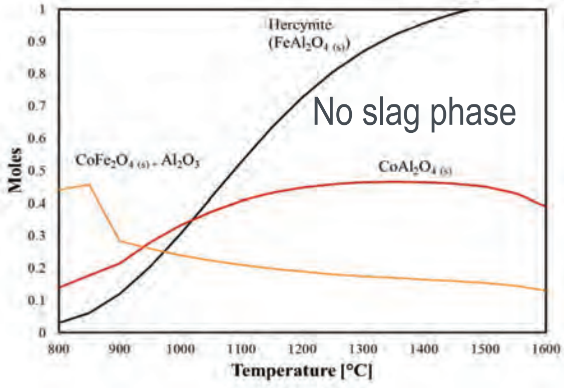
H_2O or CO_2

Heat

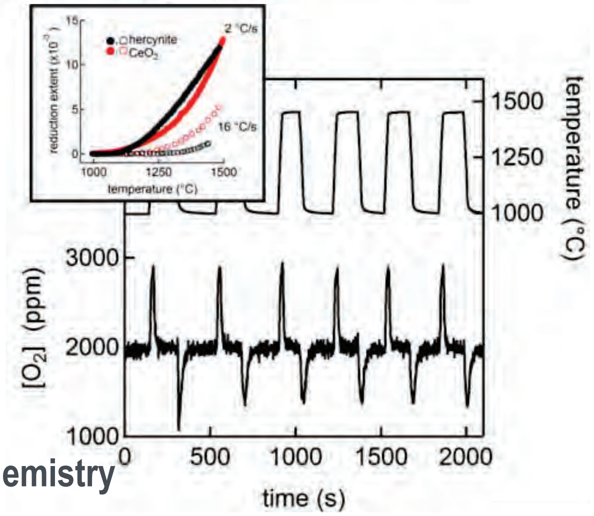
>1400 °C

O_2

$CoAl_2O_4 + FeAl_2O_4$

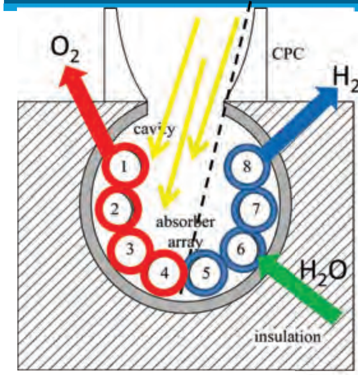


"Hercynite Cycle"



Raman spectroscopy verified cycle chemistry

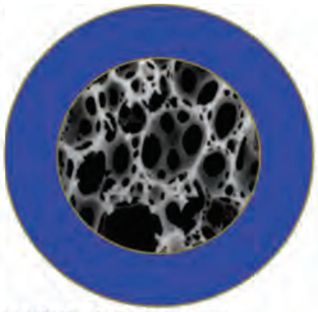
Technology Recommendations



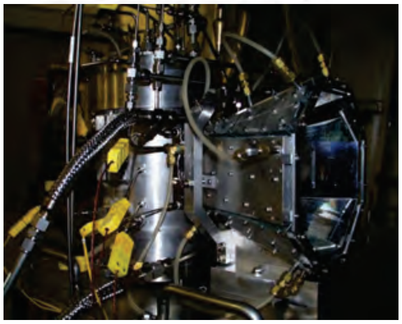
Fixed Multi-tube *Surround*Sun Reactor

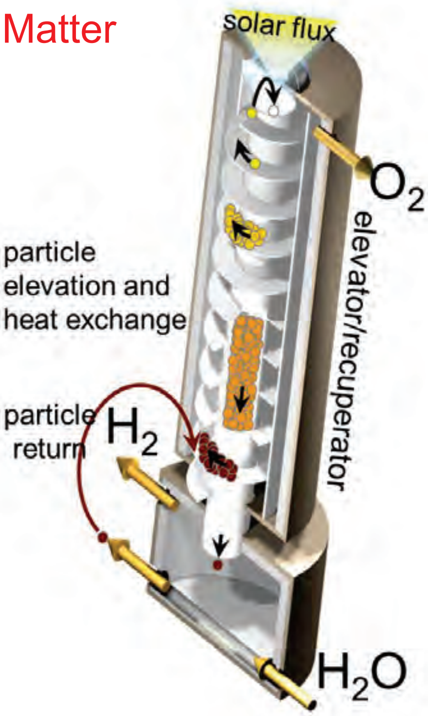
$H_2O \rightarrow H_2 + 1/2O_2$ (no bugs, no wires & no membranes; unfavorable reaction divided into two favorable reactions)

Directing Energy & Matter



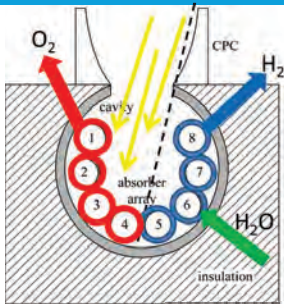
- Fast radiative heat transport
- Fast mass flow (large pores & porosity)
- Ultrathin walls to limit sensible heat loss
- Ultrathin active films to eliminate diffusional resistances (i.e. fast kinetics)



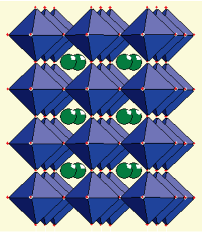


Moving Particle Bed Reactor

Insights and Recommendations



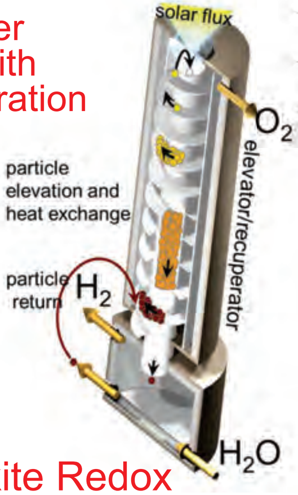
Integrate Water Desalination with Redox Heat Integration



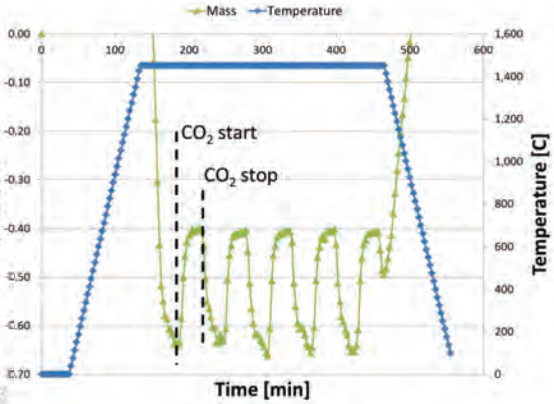
Perovskite: ABO_3

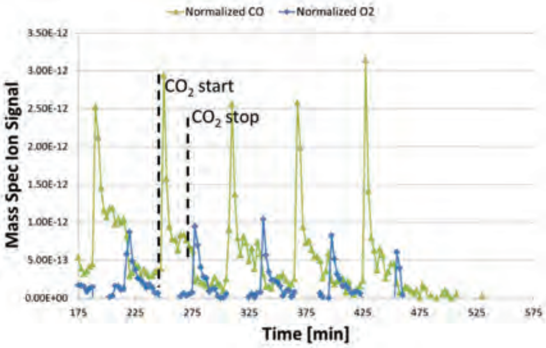
e.g. Ti-doped $SrCo_{0.8}Fe_{0.2}O_{3-\delta}$

Evaluate Perovskite Redox



Evaluate "Isothermal Redox"





WASHINGTON STATE UNIVERSITY
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Hydrogen Production from Biomass

Yong Wang

Institute for Integrated Catalysis
Pacific Northwest National Laboratory
&
Washington State University

DOE H_2 Production Expert Panel Workshop
May 10-12, 2012

Pacific Northwest
NATIONAL LABORATORY

Hydrogen Demand vs Biomass Availability

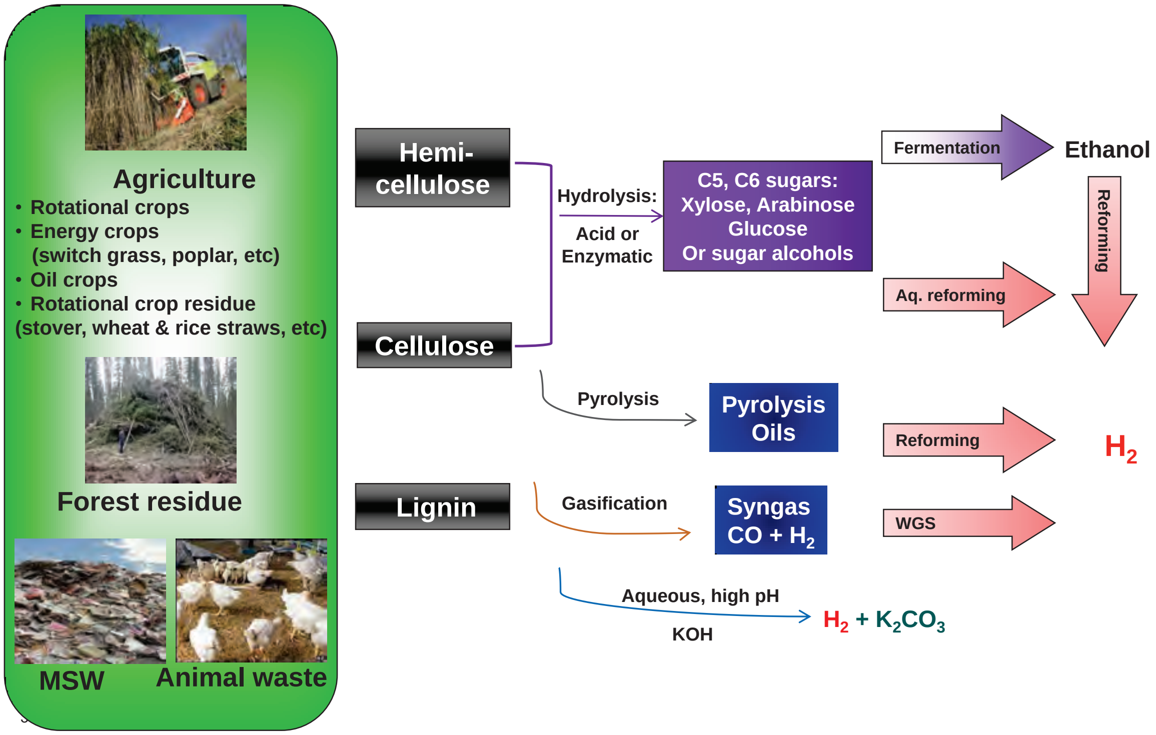
- H_2 production is ~10MMT per year in the US, is expected to grow by 5-10%/year
  - Refineries
  - NH_3 and methanol synthesis
- ~120MMT of H_2 yearly to generate the energy that oil currently provides the US
- Availability of biomass in the US
  - 1.3 billion tons/yr of non-food dry biomass available
  - → ~195MMT yearly
  - 0.5 billion tons/yr sustainably available by 2020*
  - → ~75MMT yearly

Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply

Liquid Transportation Fuels from Coal and Biomass

* *NRC report: Liquid transportation fuels from coal and biomass(2009)*

Biomass Conversion Routes to Hydrogen



Agriculture
- Rotational crops
- Energy crops
  (switch grass, poplar, etc)
- Oil crops
- Rotational crop residue
(stover, wheat & rice straws, etc)

Forest residue

MSW

Animal waste

Hemi-cellulose

Cellulose

Lignin

Hydrolysis:

Acid or Enzymatic

C5, C6 sugars:
Xylose, Arabinose
Glucose
Or sugar alcohols

Fermentation

Ethanol

Reforming

Aq. reforming

Pyrolysis

Pyrolysis Oils

Reforming

H_2

Gasification

Syngas
$CO + H_2$

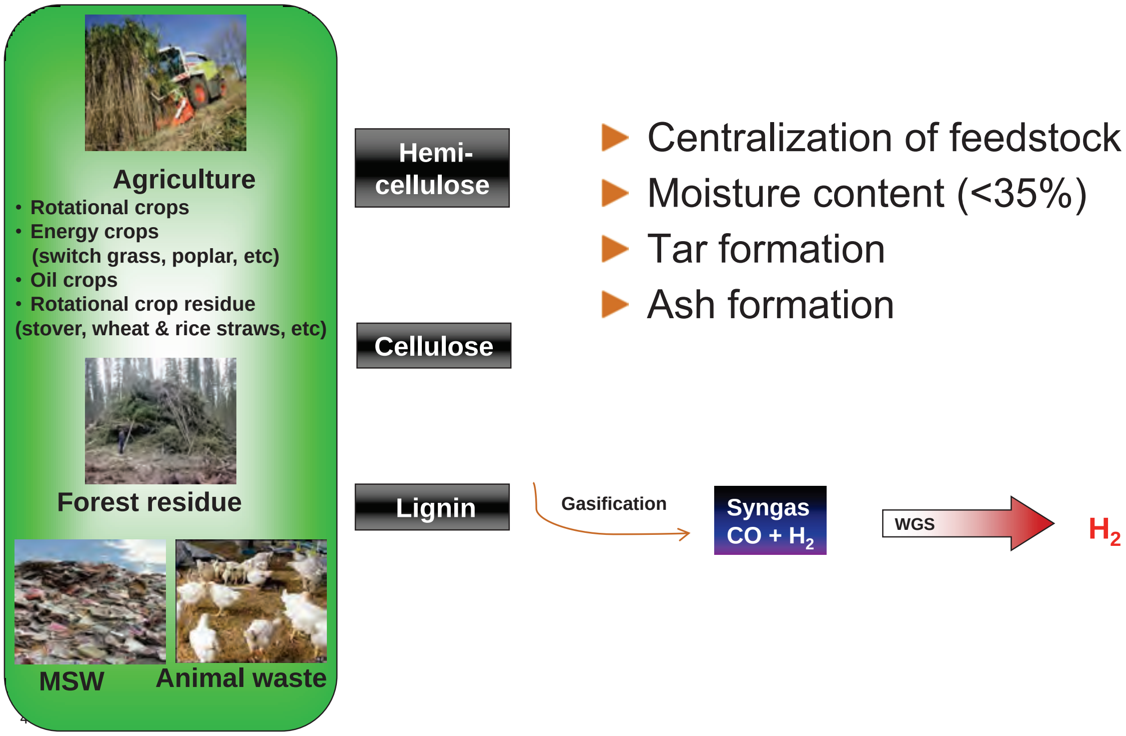
WGS

Aqueous, high pH

KOH

$H_2 + K_2CO_3$

Challenges with Gasification



- Centralization of feedstock
- Moisture content (<35%)
- Tar formation
- Ash formation

Agriculture
- Rotational crops
- Energy crops
  (switch grass, poplar, etc)
- Oil crops
- Rotational crop residue
(stover, wheat & rice straws, etc)

Forest residue

MSW

Animal waste

Hemi-cellulose

Cellulose

Lignin

Gasification

Syngas
$CO + H_2$

WGS

H_2

Bio-derived Liquids

- **Ethanol**: production via fermentation is effective in retaining hydrogen content while ejecting CO_2, and is already established as significant liquid fuel.
- **Glycerol:** byproduct production of glycerol from biodiesel production is driving glycerol price down, but availability in the US is limited.
- **Sorbitol:** price primarily driven by market for high-fructose corn syrup, but can be produced from any source of glucose.
- **Pyrolysis oil:** water soluble portion (mainly acetic acid, hydroxyl acetone) is not desirable for fuel production

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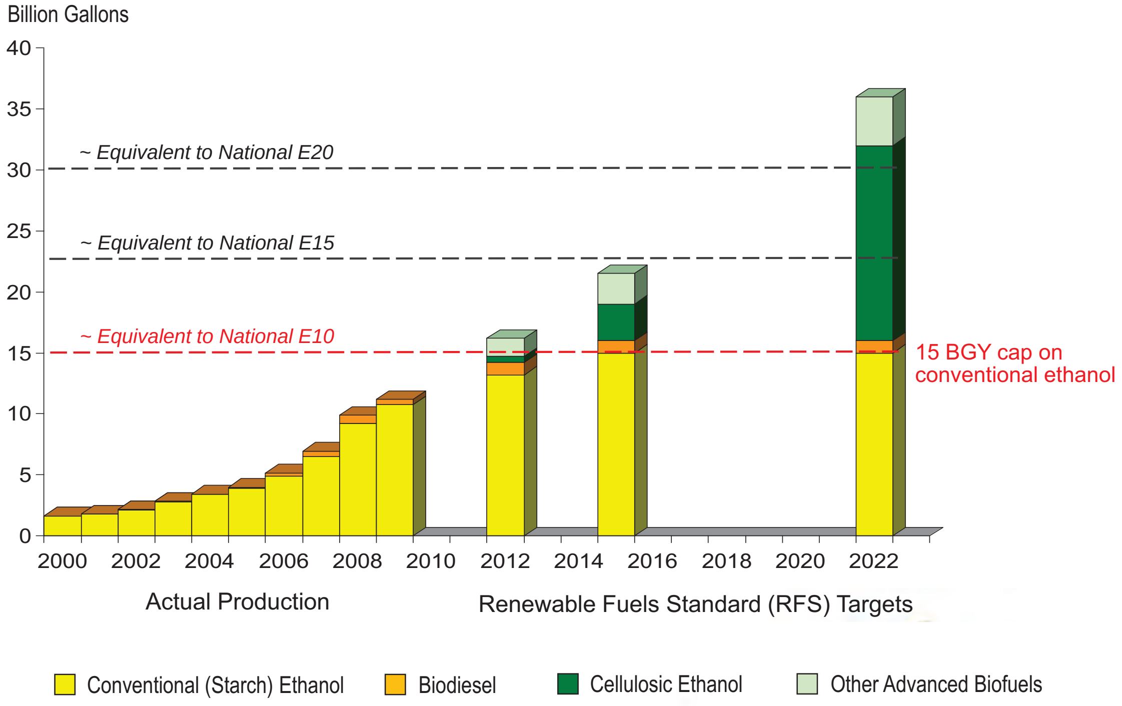
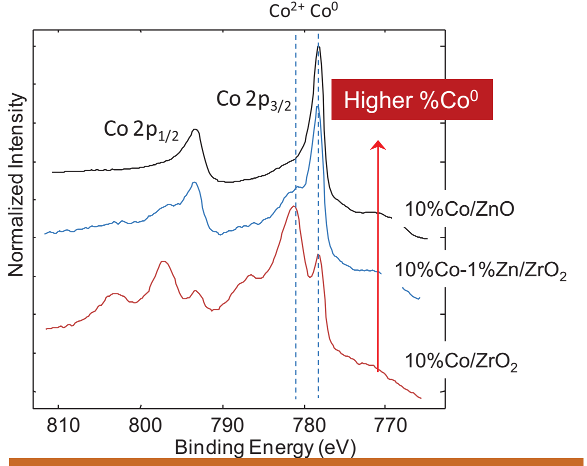
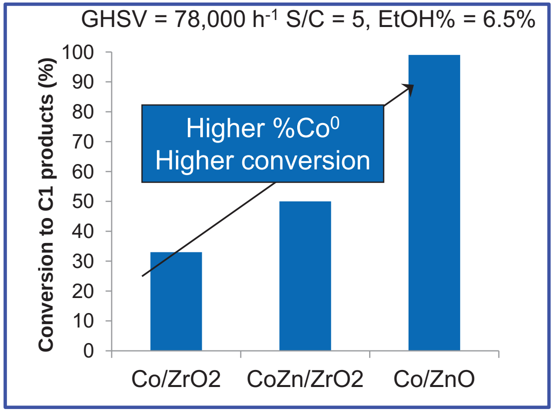
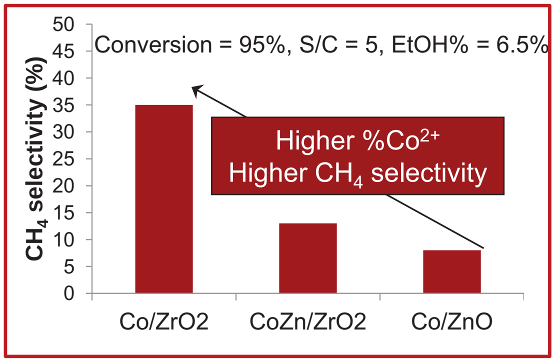
EISA Mandated U.S. Biofuels Production Targets



Highly Active and Selective Co-based Catalysts with Low CH_4 Selectivity







Challenge: ethanol feedstock accounts for ~70% hydrogen production cost

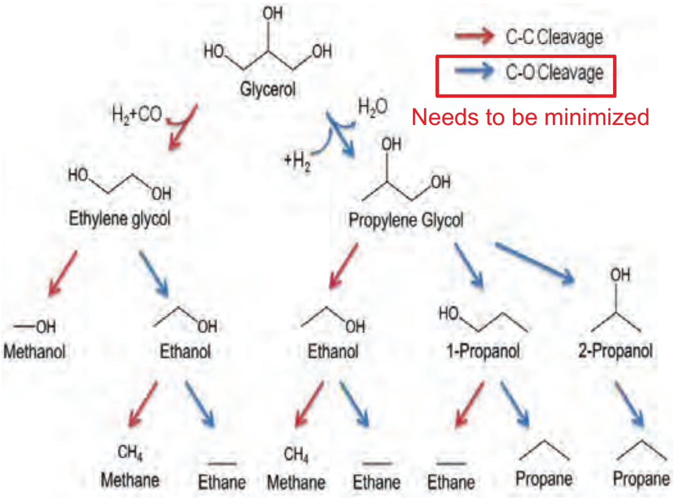
A.M.Karim, Y.Su, M.H.Engelhard, D.L.King, Y.Wang, ***ACS Catalysis,*** 2011, dx.doi.org/10.1021/cs200014j

V.Lebarbier, A.M.Karim, M.H.Engelhard, Y.Wu, B.Xu, E.Petersen, A.K.Datye, Y.Wang, ***ChemSusChem***, DOI:10.1002/cssc.201100240

Status and Challenges of H_2 Production from Bio-derived Liquids

- Bio-derived liquids are amenable for aqueous phase reforming due to high water content and poor thermal stability.
- Hydrothermal stability of catalysts including metal leaching is a major concern of catalyst life.
- Metal surface acidity derived under aqueous phase processing leads to poor selectivity and catalyst life.

Facilitating C-C Bond Breaking is Key to Hydrogen Production From Glycerol (Surrogate for Poly-oxygenates)



L. Zhang, A. M. Karim, Z. Wei, D. L. King, Y. Wang. ***J. Catal***. 287 (2012) 37-43

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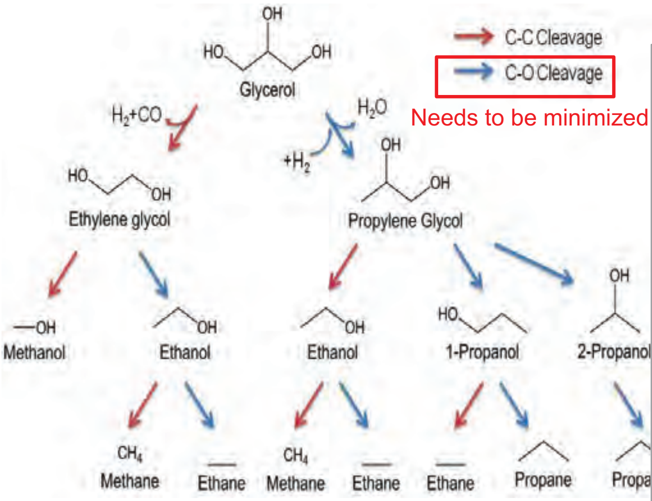

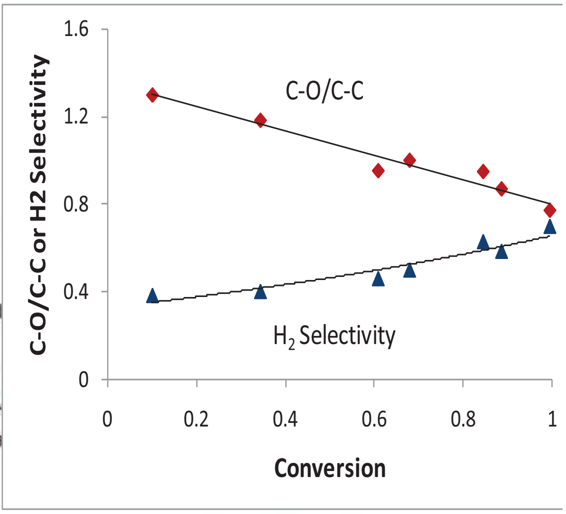

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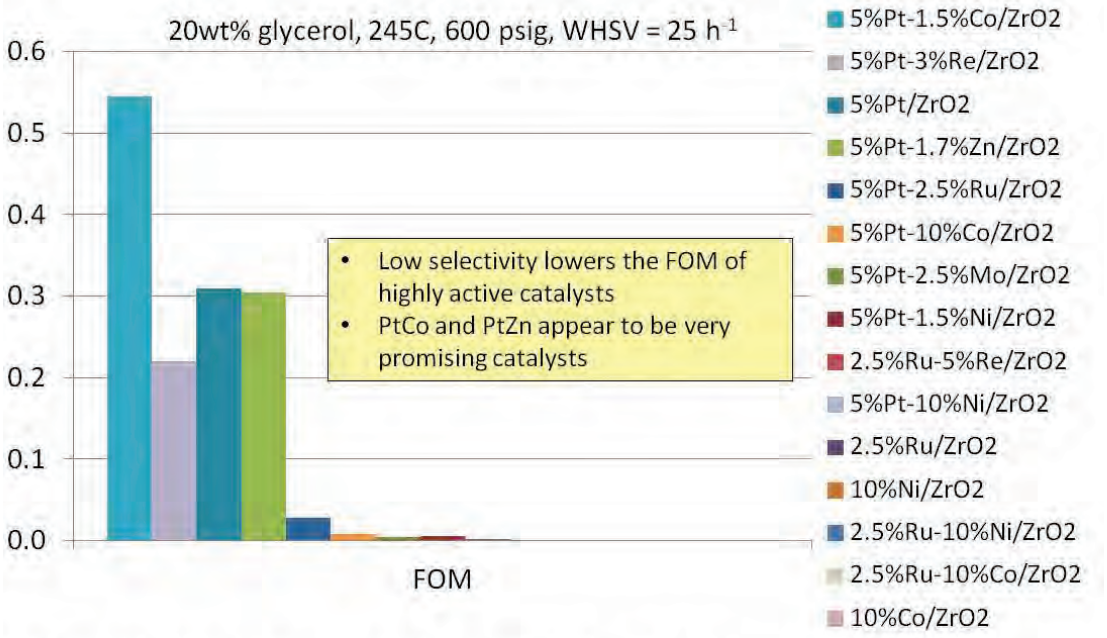
- Metal surface acidity derived under aqueous phase processing leads to poor selectivity and catalyst life
- Active catalysts are precious metal-based

APR of Glycerol on ZrO_2 Supported Catalysts



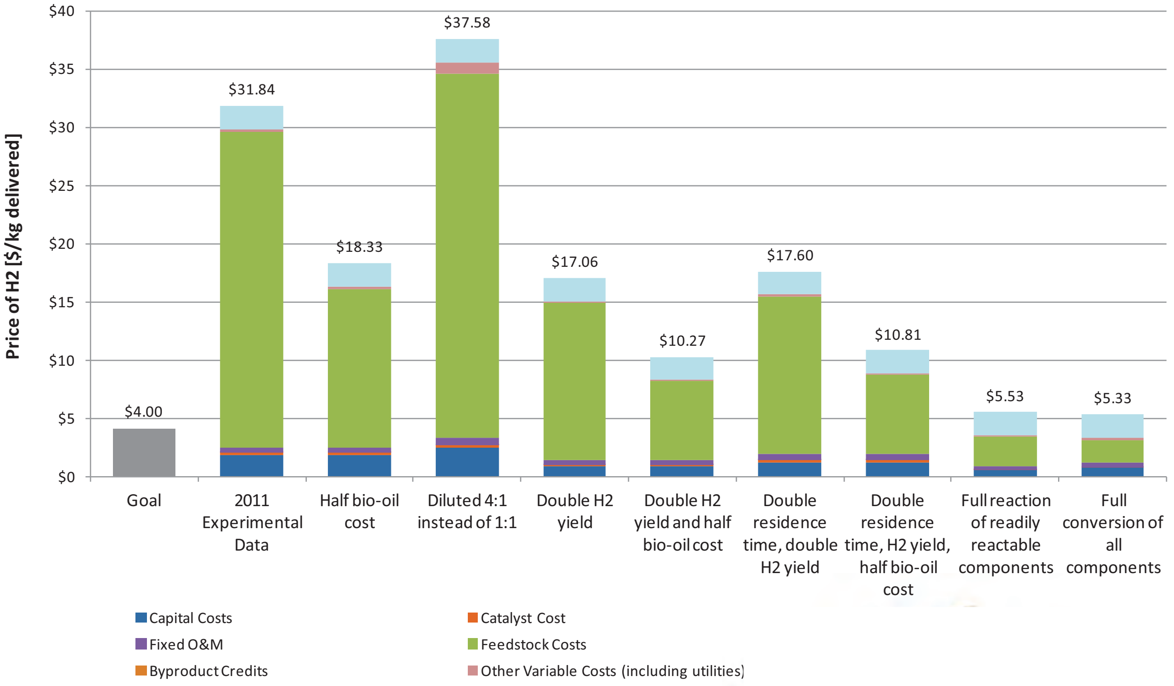
- Low selectivity lowers the FOM of highly active catalysts
- PtCo and PtZn appear to be very promising catalysts

FOM = CO_2 yield x CO_2 selectivity x H_2 yield x H_2 selectivity

Status and Challenges of H_2 Production from Bio-derived Liquids

- Bio-derived liquids are amenable for aqueous phase reforming due to high water content and poor thermal stability.
- Hydrothermal stability of catalysts including metal leaching is a major concern of catalyst life.
- Metal surface acidity derived under aqueous phase processing leads to poor selectivity and catalyst life
- Active catalysts are precious metal-based
- Sensitivity analysis of aqueous phase reforming of pyrolysis oil indicates that hydrogen production cost is mainly affected by feedstock cost and catalyst efficiency (activity/selectivity).

Sensitivity Analysis: Cost of Hydrogen From Aqueous Bio-oil APR Under Different Scenarios



Recommendations

- Production of hydrogen from low-cost and low-value feedstock
  - Directly from cellulose
  - Using water soluble portion of pyrolysis oils

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Preliminary H2A Analysis Shows Promising Cost Advantage in H_2 Production Directly from Cellulose

- Aqueous phase conversion of cellulose to ethylene glycol (61% yield) on supported WO_3 catalyst (H.Liu et al, ***Angew.Chem.Int.Ed***., DOI:10.1002/anie.201200351)
- Assuming cellulose price of $66/ton, and only taking the credit of H_2 production from ethylene glycol

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- Assuming cellulose price of $66/ton, and only taking the credit of H_2 production from ethylene glycol

Sorbitol

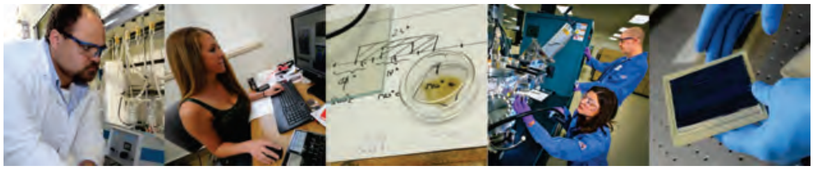
Specific Item Cost Calculation		*Total Cost of Delivered Hydrogen*	**$12.04**
Cost Component	**Hydrogen Production Cost Contribution ($/kg)**	**Compression, Storage, and Dispensing Cost Contribution ($/kg)***	**Percentage of H2 Cost**
Capital Costs	$0.75	$1.26	16.65%
Decommissioning Costs	$0.00		0.00%
Fixed O&M	$0.31	$0.46	6.46%
Feedstock Costs	$8.33		69.21%
Other Raw Material Costs	$0.00		0.00%
Byproduct Credits	$0.00		0.00%
Other Variable Costs (including utilities)	$0.76	$0.16	7.68%
Total	**$10.16**	**$1.88**	

Cellulose

Specific Item Cost Calculation		*Total Cost of Delivered Hydrogen*	**$4.13**
Cost Component	**Hydrogen Production Cost Contribution ($/kg)**	**Compression, Storage, and Dispensing Cost Contribution ($/kg)***	**Percentage of H2 Cost**
Capital Costs	$0.54	$1.26	43.71%
Decommissioning Costs	$0.00		0.00%
Fixed O&M	$0.31	$0.46	18.83%
Feedstock Costs	$0.62		15.08%
Other Raw Material Costs	$0.00		0.00%
Byproduct Credits	$0.00		0.00%
Other Variable Costs (including utilities)	$0.76	$0.16	22.39%
Total	**$2.24**	**$1.88**	

Recommendations

- Production of hydrogen from low-cost and low-value feedstock
  - Directly from cellulose
  - Using water soluble portion of pyrolysis oils
- Inexpensive catalysts with high activity and selectivity
- Stable catalysts under aqueous phase
  - Resistance to metal leaching
  - Hydrothermally stable supports
- Utilization of hydrogen generated *in situ*
- Integration with NG to contribute to the production capacity with lower or no greenhouse gas emissions without carbon sequestration technologies.



PRODUCTION OF HYDROGEN THROUGH ARTIFICIAL PHOTOSYNTHESIS

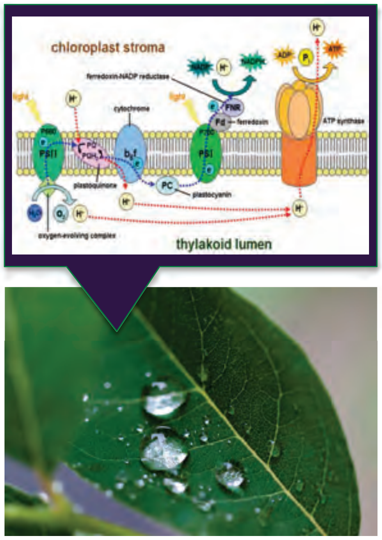
NATHAN S. LEWIS

Blue Ribbon Panel on Hydrogen Production
May 11, 2012

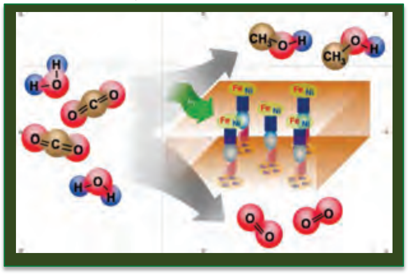
JCAP Mission

JCAP's Mission is to demonstrate a manufacturable, scalable solar-fuels generator using Earth-abundant elements that, with no wires, robustly produces fuel from the Sun ten times more efficiently than (current) crops.

Photosynthesis

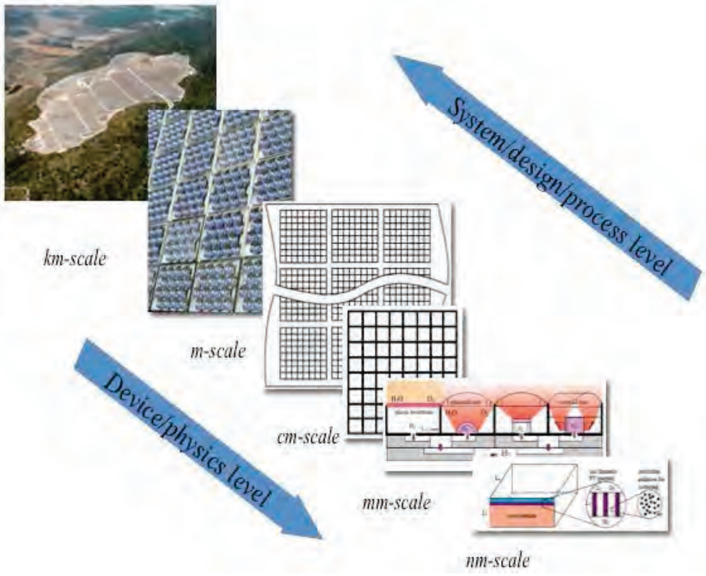


Artificial Photosynthesis



> "It is time to build an actual artificial photosynthetic system, to learn what works and what does not work, and thereby set the stage for making it work better"
>
> Melvin Calvin (1961 Nobel Prize Laureate)

JCAP Vision



- JCAP research spans efforts from fundamental discoveries of catalysts and semiconductors on the molecular or nanoscale to design and fabrication of solar-fuels generator modules that will cover kilometer-scale areas
- Efforts on these scales are performed in parallel because performance of the system on one scale affects the design choices, research thrusts, and performance targets on the other scales

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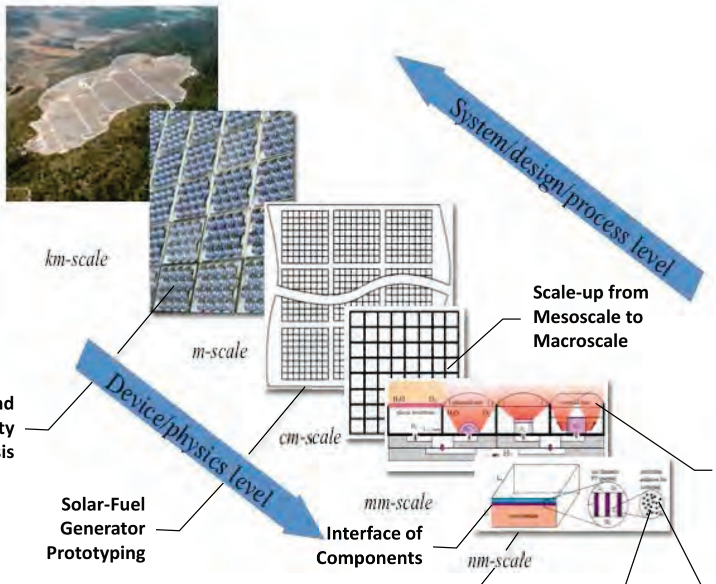
JCAP Vision – Parallel R&TD



Scale-up from Mesoscale to Macroscale

Scalability and Sustainability Analysis

Emergent Phenomena on Mesoscale

Solar-Fuel Generator Prototyping

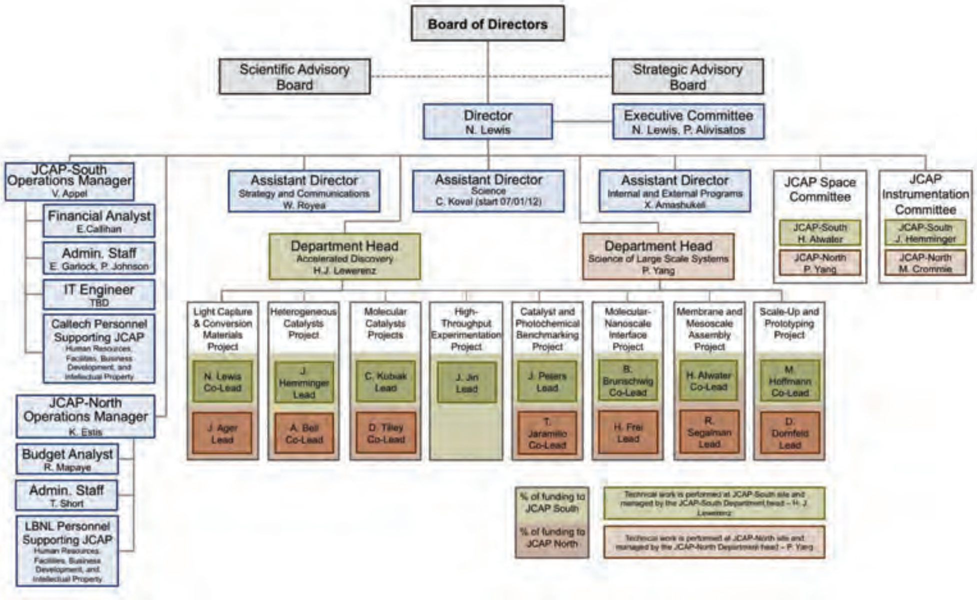
Interface of Components

Membranes

Earth-Abundant Light Capture Materials

Earth-Abundant, Low-Overpotential Catalysts

JCAP Organizational Chart



Board of Directors

Scientific Advisory Board

Strategic Advisory Board

Director
N. Lewis

Executive Committee
N. Lewis, P. Alivisatos

JCAP-South Operations Manager
V. Appel

Financial Analyst
E.Callihan

Admin. Staff
E. Garlock, P. Johnson

IT Engineer
TBD

Caltech Personnel Supporting JCAP
Human Resources, Facilities, Business Development, and Intellectual Property

JCAP-North Operations Manager
K. Estis

Budget Analyst
R. Mapaye

Admin. Staff
T. Short

LBNL Personnel Supporting JCAP
Human Resources, Facilities, Business Development, and Intellectual Property

Assistant Director
Strategy and Communications
W. Royea

Assistant Director
Science
C. Koval (start 07/01/12)

Assistant Director
Internal and External Programs
X. Amashukeli

JCAP Space Committee
JCAP-South
H. Atwater
JCAP-North
P. Yang

JCAP Instrumentation Committee
JCAP-South
J. Hemminger
JCAP-North
M. Crommie

Department Head
Accelerated Discovery
H.J. Lewerenz

Department Head
Science of Large Scale Systems
P. Yang

Light Capture & Conversion Materials Project
N. Lewis Co-Lead
J. Ager Lead

Heterogeneous Catalysts Project
J. Hemminger Lead
A. Bell Co-Lead

Molecular Catalysts Projects
C. Kubiak Lead
D. Tilley Co-Lead

High-Throughput Experimentation Project
J. Jin Lead

Catalyst and Photochemical Benchmarking Project
J. Pesers Lead
T. Jaramillo Co-Lead

Molecular-Nanoscale Interface Project
B. Brunschwig Co-Lead
H. Frei Lead

Membrane and Mesoscale Assembly Project
H. Atwater Co-Lead
R. Segalman Lead

Scale-Up and Prototyping Project
M. Hoffmann Co-Lead
D. Dornfeld Lead

% of funding to JCAP South

% of funding to JCAP North

Technical work is performed at JCAP-South site and managed by the JCAP-South Department head – H. J. Lewerenz

Technical work is performed at JCAP-North site and managed by the JCAP-North Department head – P. Yang

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Organization

The Joint Center for Artificial Photosynthesis (JCAP) is the nation's largest research program dedicated to the development of an artificial solar-fuel generation technology. Established in 2010 as a U.S. Department of Energy (DOE) Energy Innovation Hub, JCAP aims to find a cost-effective method to produce fuels using only sunlight, water, and carbon-dioxide as inputs. JCAP is led by a team from the California Institute of Technology (Caltech) and brings together more than 120 world-class scientists and engineers from Caltech and its lead partner, Lawrence Berkeley National Laboratory. JCAP also draws on the expertise and capabilities of key partners from Stanford University, the University of California campuses at Berkeley (UCB), Santa Barbara (UCSB), Irvine (UCI), and San Diego (UCSD), and the Stanford Linear Accelerator (SLAC). In addition, JCAP serves as a central hub for other solar fuels research teams across the United States, including 20 DOE Energy Frontier Research Center.

For more information, visit http://www.solarfuelshub.org.

High Temperature Electrolysis for Efficient Hydrogen Production from Nuclear Energy – INL Accomplishments and a Look to the Future

Jim O’Brien
Idaho National Laboratory

Prepared in May 2013 by the U.S. Department of Energy (DOE) Office of Nuclear Energy to provide supplemental information to the HTAC/HPEP Report regarding recent activities in the DOE Hydrogen and Fuel Cell Technologies Program (HFCTP). The HFCTP is comprised of the Office of Energy Efficiency and Renewable Energy’s Fuel Cell Technologies Office as well as hydrogen and fuel cell related programs in the Offices of Fossil Energy, Nuclear Energy and Basic Energy Sciences. After receiving the initial report submission in October 2012, the DOE disseminated the original draft to all HFCTP participants (as well as ARPA-A) requesting feedback and supplemental information that might be of technical interest to the “Hydrogen Production Expert Panel”, for future consideration. The Office of Nuclear Energy provided this supplemental information in response.

www.inl.gov

Idaho National Laboratory

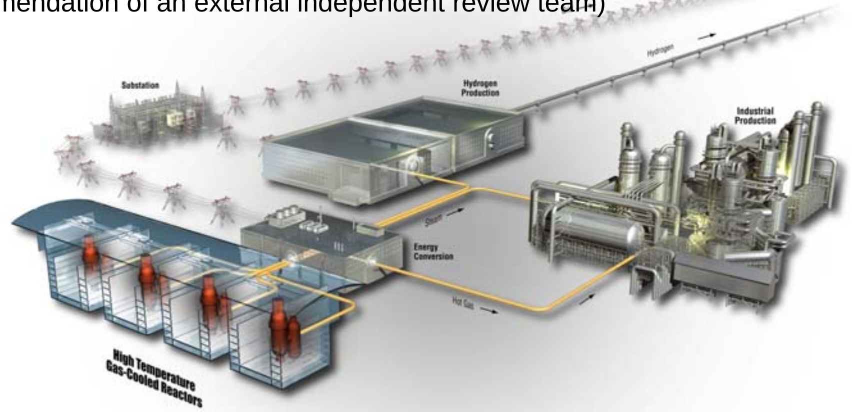
Supplemental information not included at the HPEP Workshop

Technical Concept

Idaho National Laboratory

Large-Scale Centralized Carbon-Free Nuclear Hydrogen Production based on High-Temperature Steam Electrolysis

- Directly coupled to high-temperature gas-cooled reactor for electrical power and process heat
- 600 MWth reactor could produce ~85 million SCFD hydrogen (similar to a large steam methane reforming plant) and 42 million SCFD oxygen
- Potential applications include petroleum refining, ammonia production, synthetic liquid fuels, hydrogen as a direct vehicle fuel
- During FY09, HTSE was selected by DOE as the primary nuclear hydrogen production technology for continued development toward early deployment (based on the recommendation of an external independent review team)



Supplemental information not included at the HPEP Workshop

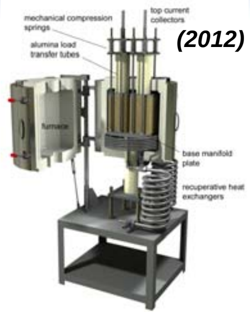
Status

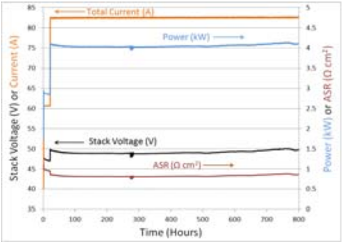
Large-Scale HTSE Demonstration

4 kW Advanced Technology HTSE test

15 kW Integrated Laboratory Scale test at INL

- Initial hydrogen production rate > 5000 NL/hr
- Demonstrated heat recuperation and hydrogen recycle
- High degradation rate





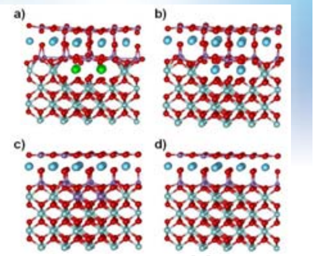
- Stable performance (<3%/khr degradation) for more than 800 hours
- Constant-current operation with a H_2 production rate of 1500 L/hr (135 gm/hr)

Supplemental information not included at the HPEP Workshop

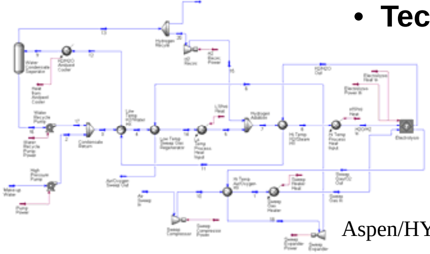
Challenges

Small stack for pressurized test

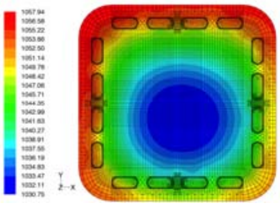
- **Fundamentals**
- **Performance Degradation**
- **CFD Simulation**
- **System Modeling and Optimization**
- **Technology Demonstration**



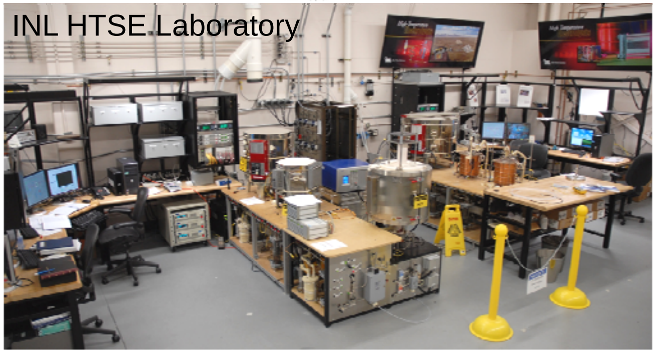
Atomistic modeling



Aspen/HYSYS model



In-stack temperature distribution



INL HTSE Laboratory

Pressurized Test

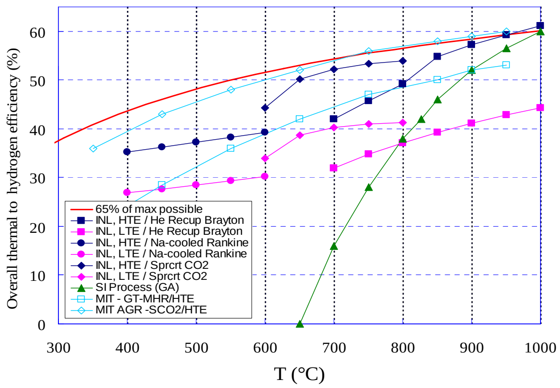
Supplemental information not included at the HPEP Workshop

Opportunities

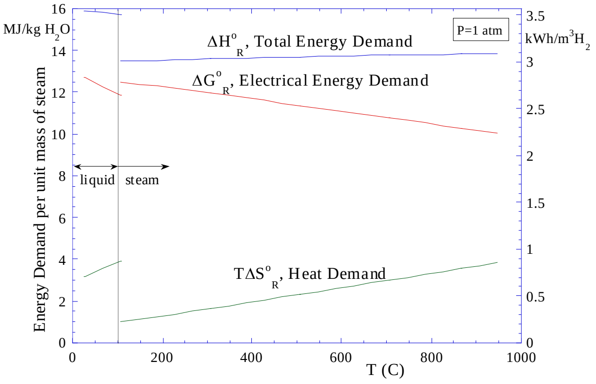
Advantages of High Temperature Operation

- Overall Thermal-to-hydrogen efficiency >50% (based on HHV)
- Electrical power requirements
  - HTE: ~ 34 kW-hr/kg
  - Conventional ~ 50 kW-hr/kg

Overall thermal-to-hydrogen production efficiencies based on HHV for several reactor/process concepts, as a function of reactor outlet temperature



Standard-state ideal energy requirements for electrolysis as a function of temperature



Supplemental information not included at the HPEP Workshop

Opportunities

Distributed Hydrogen Production Plants, Based on HTE

Economic Analysis at Forecourt-scale and Intermediate-scale

System Evaluations and Life-Cycle Cost Analyses for High-Temperature Electrolysis Hydrogen Production Facilities

Edwin A. Harvego, James E. O'Brien, Michael G. McKellar

April 2012

H2A Results Summary

(production only, not including compression, storage, and dispensing)

$/kg production cost	INL HTSE baseline	INL (with low installed cost multiplier)	NREL, conventional electrolysis (low installed cost multiplier)
forecourt scale (1500 kg/day)	3.12	2.71	4.23
intermediate-scale (50000 kg/day)	2.68	2.49	4.71
NGNP-coupled plant (200,000 kg/day)	3.23		

Note: with current low prices for natural gas, production cost for Steam-methane reforming-based production is ~$1.50/kg

Supplemental information not included at the HPEP Workshop

Conclusions

- Development of carbon-free methods for hydrogen production will be needed to meet energy security demands, especially in the transportation sector
- INL has demonstrated the feasibility of HTE for efficient hydrogen production from steam; degradation remains an issue, but significant improvements have been noted in recent tests
- FY12 pressurized testing and 4 kW demonstration advanced the technology to TRL5
- Hydrogen production costs by HTSE is almost competitive with liquid fuels, but much more expensive than SMR at present

Project Legacy

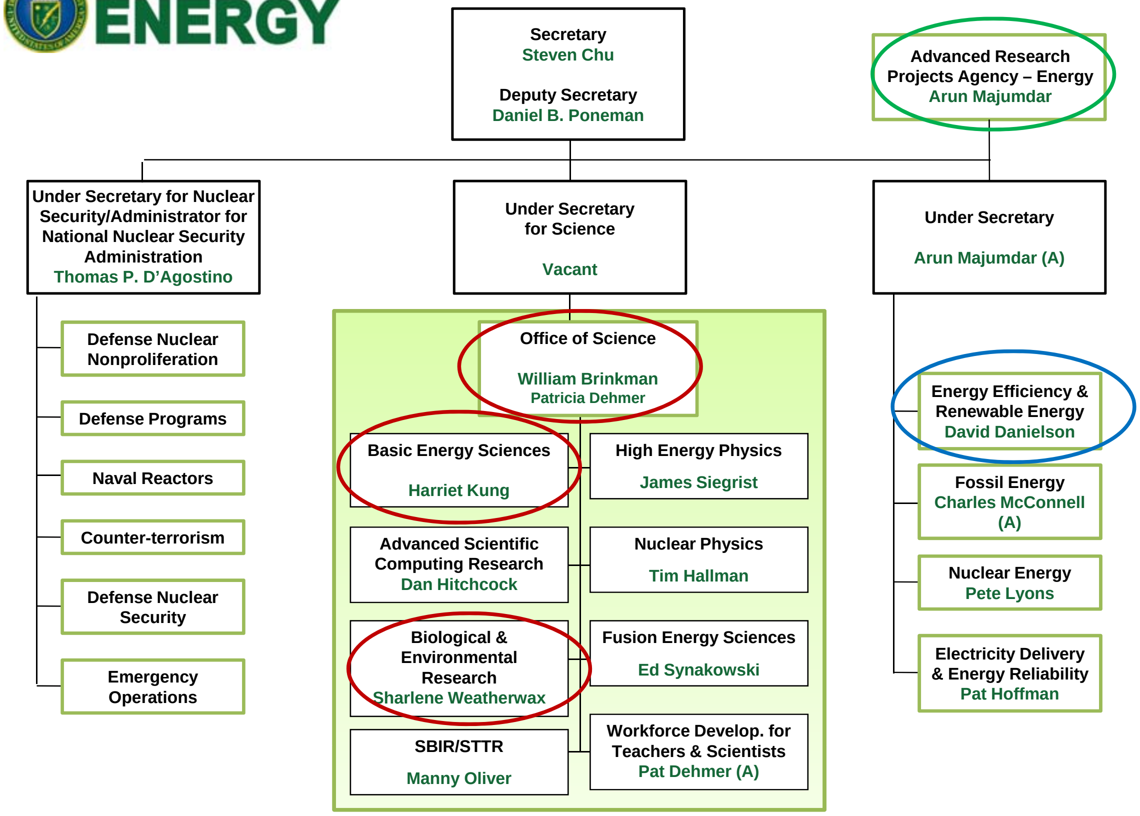
6	Book Chapters
29	Journal Articles
105	Conference papers
40	External Reports
3	US Patents

Supplemental information not included at the HPEP Workshop

Scientific Challenges and Innovative Approaches in Renewable Energy and Hydrogen Research

May 11, 2012

Richard V. Greene, Lead
Photochemistry and Biochemistry Team
Office of Basic Energy Sciences
Office of Science
U. S. Department of Energy



Secretary
Steven Chu

Deputy Secretary
Daniel B. Poneman

Advanced Research Projects Agency – Energy
Arun Majumdar

Under Secretary for Nuclear Security/Administrator for National Nuclear Security Administration
Thomas P. D'Agostino

- **Defense Nuclear Nonproliferation**
- **Defense Programs**
- **Naval Reactors**
- **Counter-terrorism**
- **Defense Nuclear Security**
- **Emergency Operations**

Under Secretary for Science
Vacant

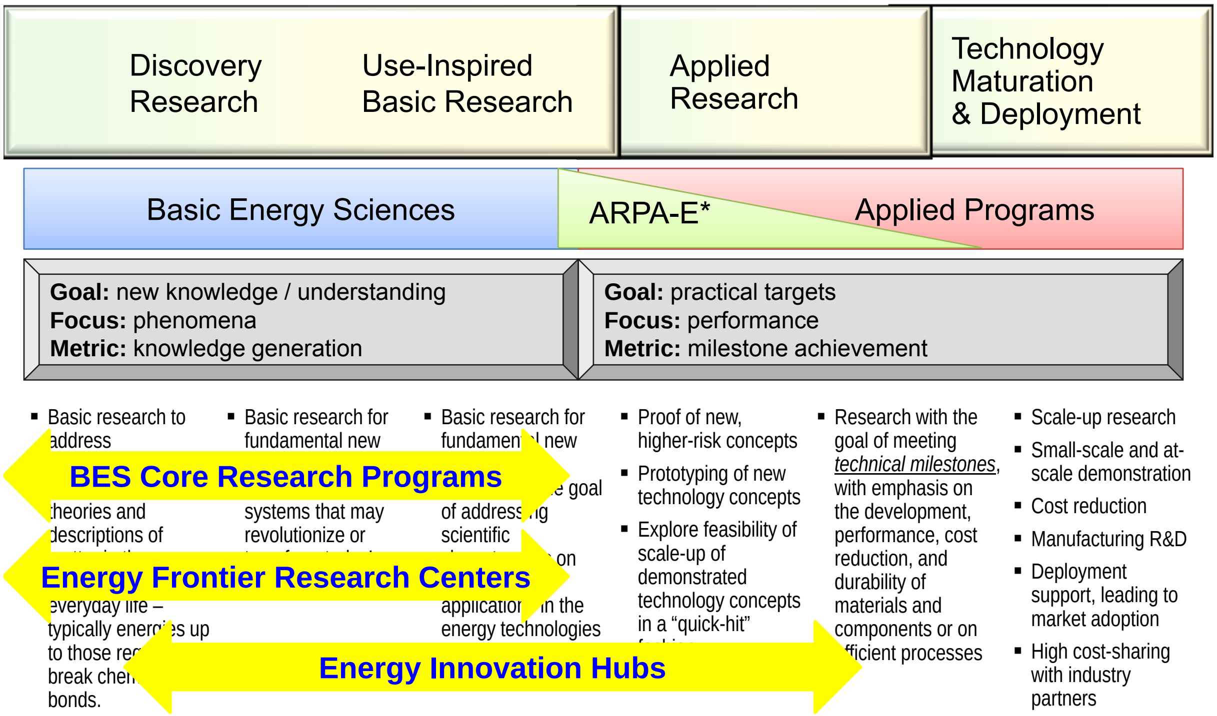
Office of Science
William Brinkman
Patricia Dehmer

- **Basic Energy Sciences** – Harriet Kung
- **High Energy Physics** – James Siegrist
- **Advanced Scientific Computing Research** – Dan Hitchcock
- **Nuclear Physics** – Tim Hallman
- **Biological & Environmental Research** – Sharlene Weatherwax
- **Fusion Energy Sciences** – Ed Synakowski
- **SBIR/STTR** – Manny Oliver
- **Workforce Develop. for Teachers & Scientists** – Pat Dehmer (A)

Under Secretary
Arun Majumdar (A)

- **Energy Efficiency & Renewable Energy** – David Danielson
- **Fossil Energy** – Charles McConnell (A)
- **Nuclear Energy** – Pete Lyons
- **Electricity Delivery & Energy Reliability** – Pat Hoffman

Continuum of Research, Development, and Deployment



Discovery Research

Use-Inspired Basic Research

Applied Research

Technology Maturation & Deployment

Basic Energy Sciences

ARPA-E*

Applied Programs

Goal: new knowledge / understanding
Focus: phenomena
Metric: knowledge generation

Goal: practical targets
Focus: performance
Metric: milestone achievement

- Basic research to address
- theories and descriptions of
- everyday life – typically energies up to those re break chen bonds.

- Basic research for fundamental new
- systems that may revolutionize or

- Basic research for fundamen l new
- e goal of address ng scientific
- on
- applicatio in the energy technologies

- Proof of new, higher-risk concepts
- Prototyping of new technology concepts
- Explore feasibility of scale-up of demonstrated technology concepts in a "quick-hit"

- Research with the goal of meeting *technical milestones*, with emphasis on the development, performance, cost reduction, and durability of materials and components or on fficient processes

- Scale-up research
- Small-scale and at-scale demonstration
- Cost reduction
- Manufacturing R&D
- Deployment support, leading to market adoption
- High cost-sharing with industry partners

U.S. DEPARTMENT OF ENERGY | Office of Science

* ARPA-E: targets technology gaps, high-risk concepts, aggressive delivery times

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Platinum Monolayer Electro-Catalysts:

Stationary and Automotive Fuel Cells

Basic Science

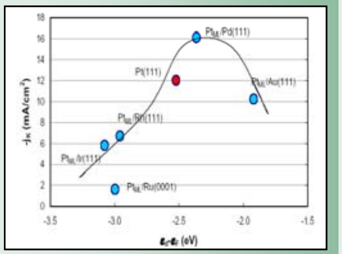
Applied R&D

Manufacturing/ Commercialization

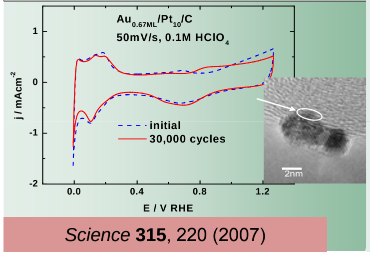
BES

Two research advances

Pt core-shell nano-catalysts: high activity with ultralow Pt mass



Pt stabilized against corrosion in voltage cycling by Au clusters



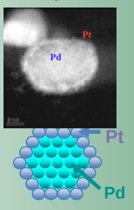
Science **315**, 220 (2007)

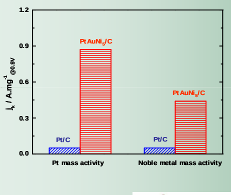
BES → EERE

Core-Shell Nanocatalysts

Active Pt ML shell – Metal/alloy core
Core tunes activity & durability of shell

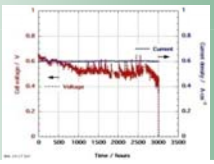
Model and actual image of a Pt Monolayer on Pd nanoparticle





Pt-mass weighted activity enhanced 20x

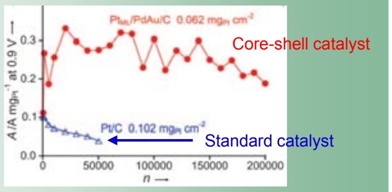
3000 hr Fuel Cell Durability Performance



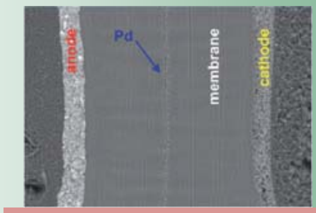
CRADA with Industry

Scale-up synthesis: **Pt-ML/Pd_9Au_1/C**

Excellent fuel Cell durability 200,000 cycles



Membrane Electrode Assembly >200K cycles
Very small Pt diffusion & small Pd diffusion



Angewandte Chemie ***49****, 8602 (2010)*

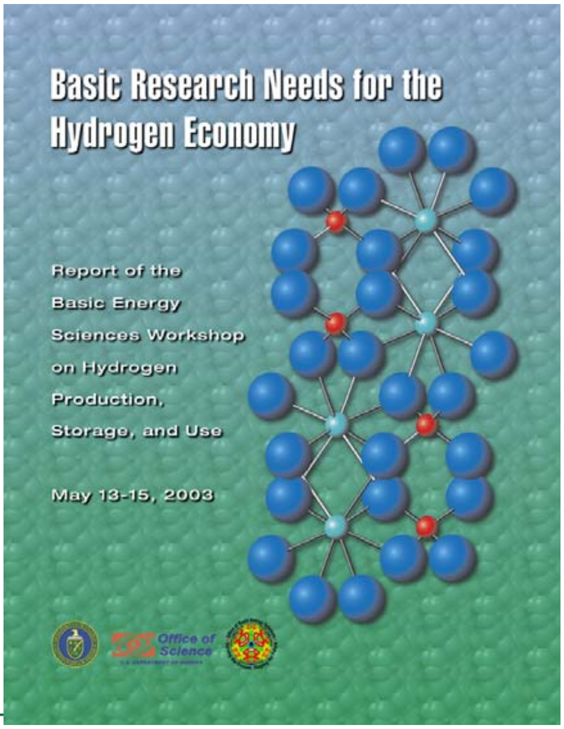
Fuel Cell Catalyst readied for automotive application

Basic Energy Sciences Strategic Planning Exercise

Utilizing scientific expertise developed over a quarter century through basic research on problems in hydrogen and fuel cells, BES convened a panel of experts in 2003 to identify and outline areas of basic research critical to the development of hydrogen as an energy source for the U.S. economy.

In this Basic Research Needs Workshop the topics of Hydrogen Production, Storage, Transport, and Use were discussed and explored.

High Priority Research Directions were identified and defined.



Basic Research Needs for the Hydrogen Economy

Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use

May 13-15, 2003

U.S. DEPARTMENT OF ENERGY | Office of Science

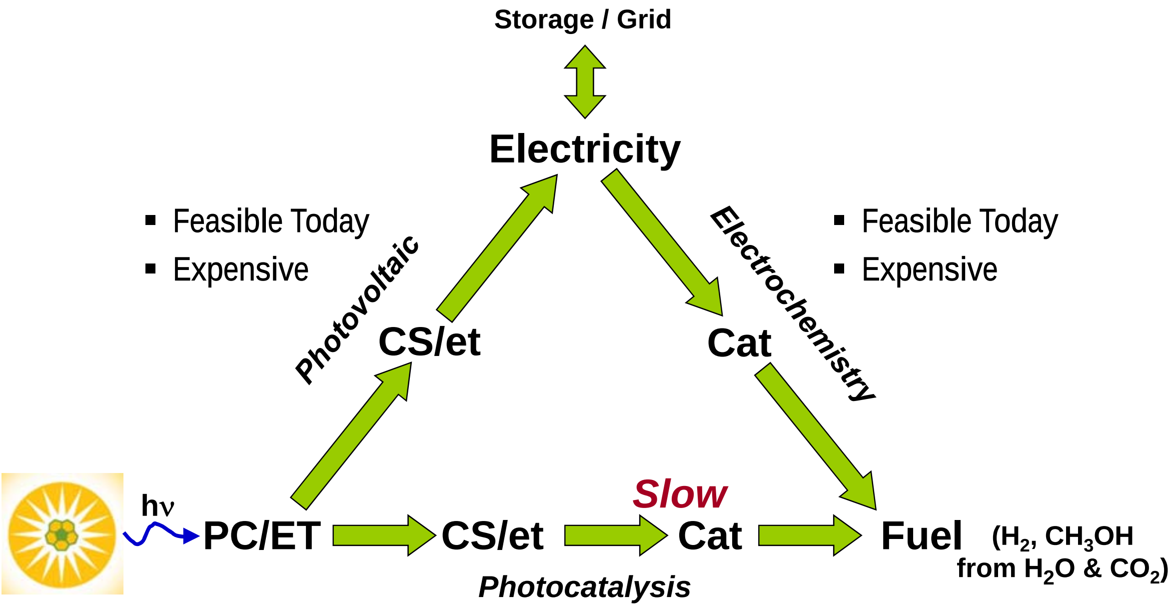
BES Priority Hydrogen Research Directions

- Low-Cost and Efficient Solar Energy Production of Hydrogen Nanoscale Catalyst Design
- Biological, Biomimetic, and Bio-inspired Materials and Processes
- Complex Hydride Materials for Hydrogen Storage
- Nanostructured and Other Novel Hydrogen Storage Materials
- Theory, Modeling, and Simulation of Materials and Molecular Processes
- Low-Cost, Highly Active, Durable Cathodes for Low-Temperature Fuel Cells
- Membranes and Separation Processes for Hydrogen Production and Fuel Cells
- Analytical and Measurement Technologies
- Impact of the Hydrogen Economy on the Environment
- Safety in the Hydrogen Economy

Hydrogen production-related topics

U.S. DEPARTMENT OF ENERGY | Office of Science

Fuels from Sunlight



- Feasible Today
- Expensive

- Feasible Today
- Expensive

Key

Photon capture and energy transfer	PC/ET
Charge separation and electron transport	CS/et
Catalysis and fuel formation	Cat

- Work in Progress
- Economically Attractive

Fuels from Sunlight

More Energy from Sunlight Strikes the Earth in an Hour than All the Energy Consumed on the Planet in a Year!!!

BES Biological Hydrogen Production Research

Current areas of supported research include:

- Investigating cell metabolism and regulatory networks in photosynthetic and heterotrophic bacteria, algae and Archaea for improved hydrogen production
- Understanding assembly, structure and function of hydrogenase and nitrogenase enzymes
- Developing photobiohybrid structures based on natural biological systems and enzymes

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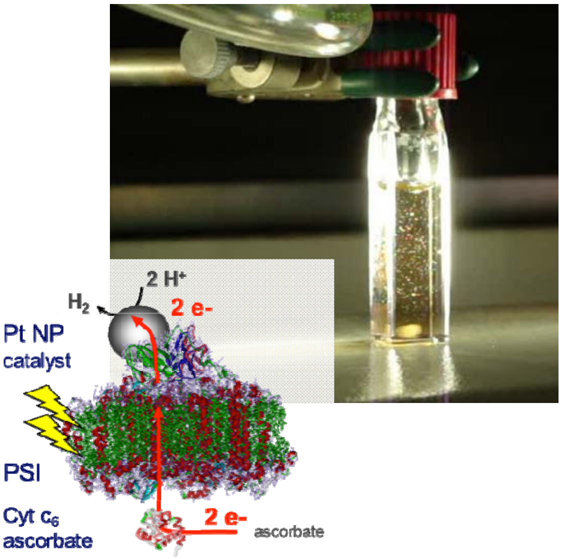
Photo-driven hydrogen production via a noncovalent biohybrid protein complex



Lisa Utschig, Argonne National Laboratory
J. Phys. Chem. Letts. (2011) 2: 236
C&E News January 31, 2011

- Using BES funding, researchers developed a Photosystem I (PSI) - platinum (Pt) nanoparticle hybrid system that photocatalytically generated hydrogen at a rate five times greater than the previous record-setting system.
- The study demonstrates that highly efficient photocatalysis of hydrogen can be obtained for a self-assembled, noncovalent complex between one of Nature's specialized energy converters, PSI, and Pt nanoparticles.
- The results suggest a new strategy for linking molecular catalysts to PSI that takes advantage of electrostatic-directed assembly to mimic acceptor protein binding.

BES Non-Biological Hydrogen Production Research

Current areas include:

- Low-Cost and Efficient Production of Hydrogen through Nanoscale Catalyst Design, using both electrochemical and photochemical systems
- Biomimetic and Bio-inspired Materials and Processes
- Theory, Modeling and Simulation of Materials and Molecular Processes

Fundamental knowledge from DOE-supported studies addresses:

- ***Structure:*** How can molecular structure and nanostructures be manipulated to optimize water splitting for hydrogen production?
- ***Energetics:*** How can we produce excited states in molecular and solid catalysts with the energetics to reduce hydrogen?
- ***Dynamics:*** What are the physical models that connect the kinetics of a catalyst with its structure and energetics?
- ***Theory:*** How can research and discovery be accelerated through theory and computational modeling?

Core research in hydrogen production is bolstered by several EFRCs and the Fuels from Sunlight Hub

U.S. DEPARTMENT OF ENERGY | Office of Science

Photoinitiated Electron Collection in Mixed-Metal Supramolecular Complexes

Scientific Goal

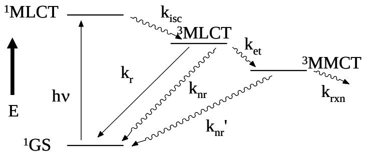
Development of photocatalysts for hydrogen production by design and study of supra-molecular complexes to produce hydrogen from H_2O using molecular devices for photoinitiated electron collection

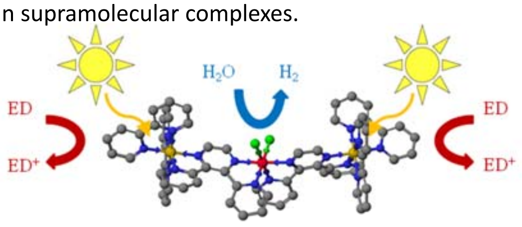
Significance and Impact

Hydrogen evolution from water requires multiple electrons to be photogenerated and transported; these studies lead to an understanding of processes which can accomplish the multielectron reduction of chemical species to produce fuel.

Research Details

- Probe the role of sub-unit variation on the functioning of supramolecular H_2 production photocatalysts to explore the impact of modulation of orbital energetics and excited state dynamics on this complicated photochemistry
- Develop a fundamental understanding of the rates and mechanisms of multielectron photochemistry and photocatalysis in supramolecular complexes.





T. A. White, B. N. Whitaker and K. J. Brewer,
J. Am. Chem. Soc., **2011**, 133(39) 15332-15334.

U.S. DEPARTMENT OF ENERGY | Office of Science

Virginia Tech

New Catalyst Speeds Conversion of Electricity to Hydrogen Fuel

Scientific Achievement

A newly synthesized Nickel complex speeds the production of hydrogen ten times faster than a natural hydrogenase enzyme at room temperature.

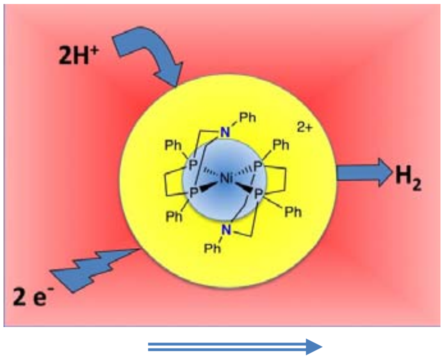
Significance and Impact

Opens a new research path to develop long-lived catalysts using inexpensive, earth-abundant metals to convert electrical energy to chemical energy.

Research Details

- In this process, water molecules are split to produce hydrogen and oxygen. Hydrogen can be used as a fuel.
- Using the natural hydrogenase enzyme as a model, a synthetic catalyst using Nickel was developed. The metal atom gets its reactive properties from the groups of atoms containing phosphorous and nitrogen that surround it.
- By splitting water, hydrogen gas is formed by combining the H^+ on the nitrogen with the H^- on the nickel center.
- Adding an acid or water increased the rate of hydrogen produced from the newly-designed synthetic catalyst.

ML Helm, MP Stewart, RM Bullock, MR DuBois, DL DuBois Science **12 August 2011**: 863. Work was supported by the Center for Molecular Electrocatalysis, an EFRC led by Pacific Northwest National Laboratory.

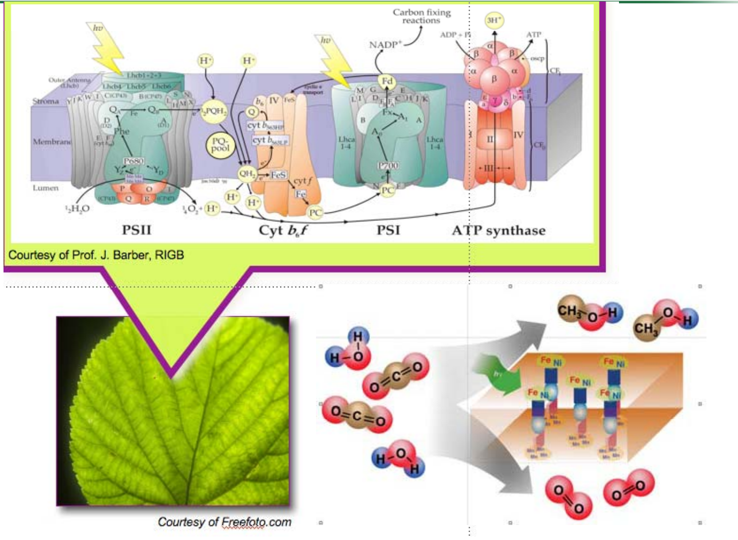


$2\ e^- + 2\ H^+ \rightarrow H_2$

Schematic showing catalyst operation

Fuels from Sunlight Hub (Joint Center for Artificial Photosynthesis)

The objective of the Fuels from Sunlight Hub is to develop an effective solar energy to chemical fuel conversion system. The system should operate at an overall efficiency and produce fuel of sufficient energy content to enable transition from bench-top discovery to proof-of-concept prototyping.



Courtesy of Prof. J. Barber, RIGB

Courtesy of Freefoto.com

<u>JCAP Mission:</u> To demonstrate a scalable, manufacturable solar-fuels generator using Earth-abundant elements, that, with no wires, robustly produces fuel from the sun ten times more efficiently than (current) crops.

JCAP Director is Professor Nate Lewis. Funding is approximately $120M over five years. Centered at CalTech and LBNL

Fuels from Sunlight: Critical Issues in Research

fs

Photon absorption and harvesting

How do we control light harvesting to utilize all of the photons?

-Need to know how to design and control exciton transfer in molecular systems

-Need red absorbers to harvest the bulk of the solar spectrum

ps-ns

Charge separation and transport

How do we avoid recombination of photo-generated charge carriers?

-Need to overcome geminate recombination in organic systems

-Need to design transport to reduce non-geminate recombination in all systems

μs-ms

Photocatalysis

How do we produce fuels with the energy provided by visible light absorption?

-Need hetero/homo -geneous catalytic systems for water splitting

-Need to couple light absorption to catalytic processes for C-C bond formation

Challenges of this magnitude require a long-term commitment to fundamental research

U.S. DEPARTMENT OF ENERGY | Office of Science

Fuel Cell Technologies Program

Hydrogen Production Expert Panel Workshop

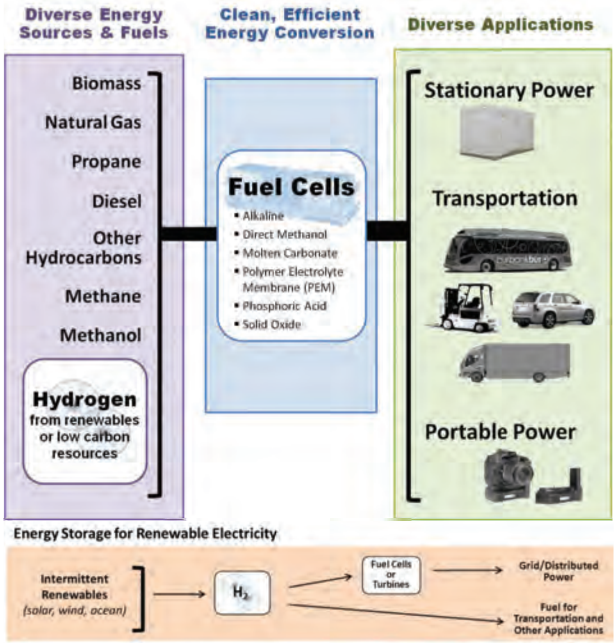
- a subcommittee of the Federal Hydrogen And Fuel Cell Technical Advisory Committee (HTAC)

May 11, 2012

Sunita Satyapal & Eric Miller

Fuel Cell Technologies Program
Energy Efficiency and Renewable Energy
U.S. Department of Energy

Hydrogen: Sources & Applications

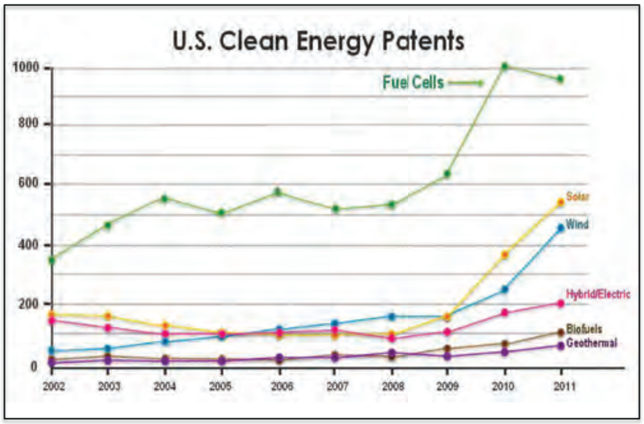


Key Benefits

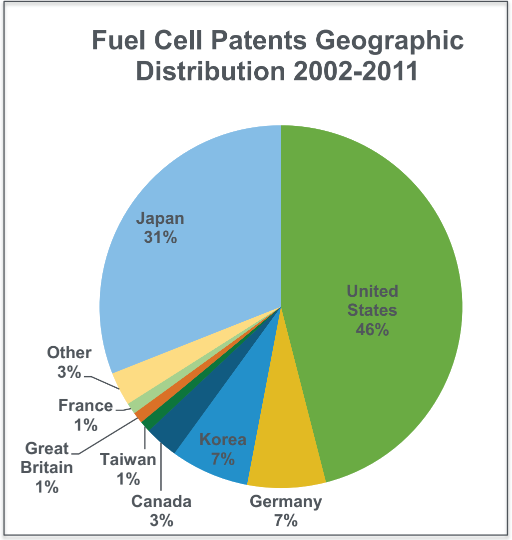
Very High Efficiency	• **> 60%** *(electrical)* • **> 70%** *(electrical, hybrid fuel cell / turbine)* • **> 80%** *(with CHP)*
Reduced CO_2 Emissions	• **35–50%+ reductions** *for CHP systems (>80% with biogas)* • **55–90% reductions** *for light-duty vehicles*
Reduced Oil Use	• **>95% reduction** *for FCEVs (vs. today's gasoline ICEVs)* • **>80% reduction** *for FCEVs (vs. advanced PHEVs)*
Reduced Air Pollution	• **up to 90% reduction in criteria pollutants** *for CHP systems*
Fuel Flexibility	• **Clean fuels** — *including biogas, methanol, H_2* • **Hydrogen** — *can be produced cleanly using sunlight or biomass directly, or through electrolysis, using renewable electricity* • **Conventional fuels** — *including natural gas, propane, diesel*

Hydrogen can play important role in the transport, storage and efficient conversion of renewable energy in the President's "all of the above" energy strategy.

Emerging Fuel Cell Industries Further Increase the Demand for Hydrogen



Top 10 companies: Honda, GM, Toyota, UTC Power, Samsung, Ballard, Nissan, Plug Power, Delphi Technologies, Matsushita Electric Industrial



Clean Energy Patent Growth Index[1] shows that fuel cell patents lead in the clean energy field with nearly 1,000 fuel cell patents issued worldwide in 2010, 3x more than the second place holder (solar); Number of fuel cell patents grew > 57% in 2010.

The growing demand, along with increasing economic and environmental pressures, necessitate the development and adoption of new technologies for the affordable large-scale production of low-carbon hydrogen

[1] http://cepgi.typepad.com/heslin_rothenberg_farley_/

Worldwide Commitment to FCEVs

The world's leading automakers have committed to develop FCEVs. Germany and Japan have announced plans to expand the hydrogen infrastructure.

Major Auto Manufacturers' Activities and Plans for FCEVs

Toyota	• 2010-2013: U.S. demo fleet of 100 vehicles • 2015: Target for large-scale commercialization • "FCHV-adv" can achieve 431-mile range and 68 mpgge
Honda	• Clarity FCX named "World Green Car of the Year"; EPA certified 72mpgge; leasing up to 200 vehicles • 2015: Target for large-scale commercialization
Daimler	• Small-series production of FCEVs began in 2009 • Plans for tens of thousands of FCEVs per year in 2015 – 2017 and hundreds of thousands a few years after • In partnership with Linde to develop fueling stations. • ***Recently moved up commercialization plans to 2014***
General Motors	• 115 vehicles in demonstration fleet • 2012: Technology readiness goal for FC powertrain • 2015: Target for commercialization
Hyundai-Kia	• 2012-2013: 2000 FCEVs/year • 2015: 10,000 FCEVs/year • "Borrego" FCEV has achieved >340-mile range.
Volkswagen	• Expanded demo fleet to 24 FCEVs in CA • Recently reconfirmed commitment to FCEVs
SAIC (China)	• Partnering with GM to build 10 fuel cell vehicles in 2010
Ford	• Alan Mulally, CEO, sees 2015 as the date that fuel cell cars will go on sale.
BMW	• BMW and GM plan to collaborate on the development of fuel cell technology

Based on publicly available information during 2011

H_2Mobility - evaluate the commercialization of H_2 infrastructure and FCEVs

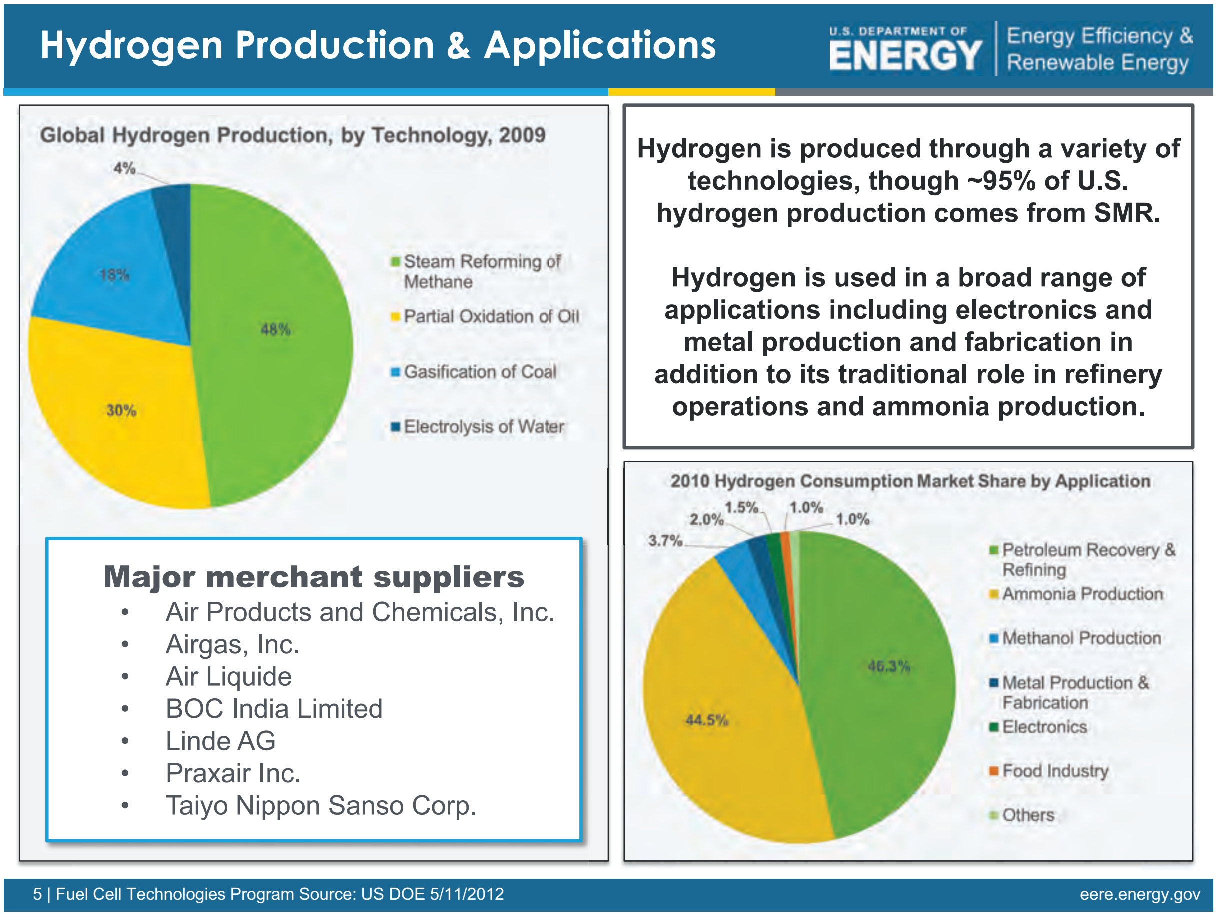
- Public-private partnership between NOW and 9 industry stakeholders including:
  - Daimler, Linde, OMV, Shell, Total, Vattenfall, EnBW, Air Liquide, Air Products
- FCEV commercialization by 2015.

UKH_2Mobility will evaluate anticipated FCEV roll-out in 2014/2015

- 13 industry partners including:
  - Air Liquide, Air Products, Daimler, Hyundai, ITM Power , Johnson Matthew, Nissan, Scottish & Southern Energy, Tata Motors, The BOC Group, Toyota, Vauxhall Motors
- 3 UK government departments
- Government investment of £400 million to support development, demonstration, and deployment.

13 companies and Ministry of Transport announce plan to commercialize FCEVs by 2015

- 100 refueling stations in 4 metropolitan areas and connecting highways planned, 1,000 station in 2020, and 5,000 stations in 2030.



Hydrogen Production & Applications

Global Hydrogen Production, by Technology, 2009

- 🟩 Steam Reforming of Methane
- 🟨 Partial Oxidation of Oil
- 🟦 Gasification of Coal
- ■ Electrolysis of Water

Hydrogen is produced through a variety of technologies, though ~95% of U.S. hydrogen production comes from SMR.

Hydrogen is used in a broad range of applications including electronics and metal production and fabrication in addition to its traditional role in refinery operations and ammonia production.

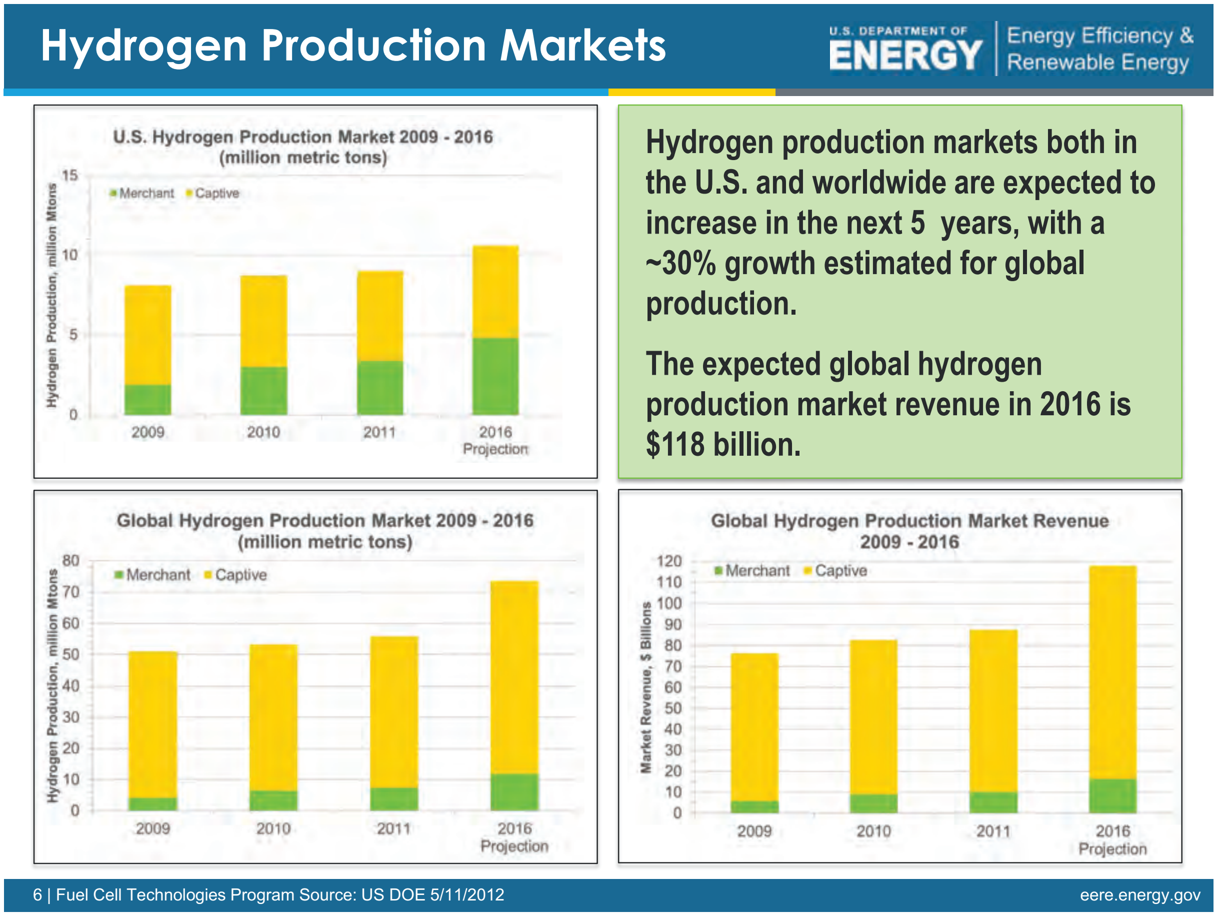
Major merchant suppliers

- Air Products and Chemicals, Inc.
- Airgas, Inc.
- Air Liquide
- BOC India Limited
- Linde AG
- Praxair Inc.
- Taiyo Nippon Sanso Corp.

2010 Hydrogen Consumption Market Share by Application

- 🟩 Petroleum Recovery & Refining
- 🟨 Ammonia Production
- 🟦 Methanol Production
- ■ Metal Production & Fabrication
- ■ Electronics
- 🟧 Food Industry
- ■ Others

5 | Fuel Cell Technologies Program Source: US DOE 5/11/2012 eere.energy.gov



Hydrogen Production Markets

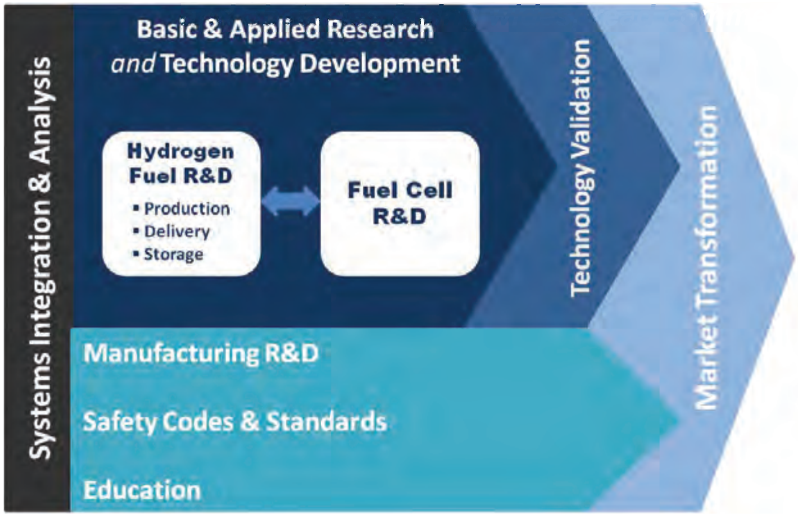
Hydrogen production markets both in the U.S. and worldwide are expected to increase in the next 5 years, with a ~30% growth estimated for global production.

The expected global hydrogen production market revenue in 2016 is $118 billion.

6 | Fuel Cell Technologies Program Source: US DOE 5/11/2012 eere.energy.gov

DOE R&D in Hydrogen and Fuel Cells

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



WIDESPREAD COMMERCIALIZATION ACROSS ALL SECTORS

- Transportation
- Stationary Power
- Auxiliary Power
- Backup Power
- Portable Power

Nearly 300 projects currently funded

at companies, national labs, and universities/institutes

FY12 EERE H_2 and Fuel Cells Budget: $104M

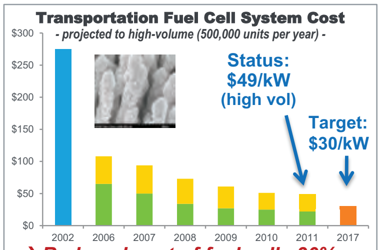
Federal Role in Fuel Cells: RD&D to Deployments

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

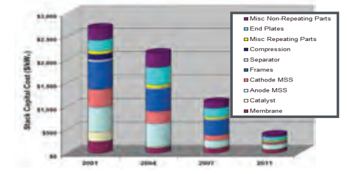
DOE R&D

- *Reduces cost and improves performance*

Examples:



→ Reduced cost of fuel cells 30% since 2008, 80% since 2001



→ Reduced cost of electrolyzer stacks 60% since 2007

DOE Demonstrations & Technology Validation

- *Validate advanced technologies under real-world conditions*
- *Feedback guides R&D*

Examples—validated:

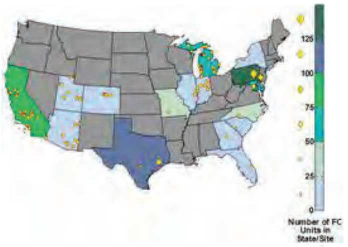
- ***59% efficiency***
- ***254 mile range (independently validated 430-mile range)***
- ***75,000-mi durability***

Program also includes enabling activities such as codes & standards, analysis, and education.

Deployments

- ***Market Transformation***
- ***DOE Recovery Act Projects***
- ***Government Early Adoption (DoD, FAA, California, etc.)***
  - ***IDIQ****
- ***Tax Credits: 1603, 48C***

Recovery Act & Market Transformation Deployments

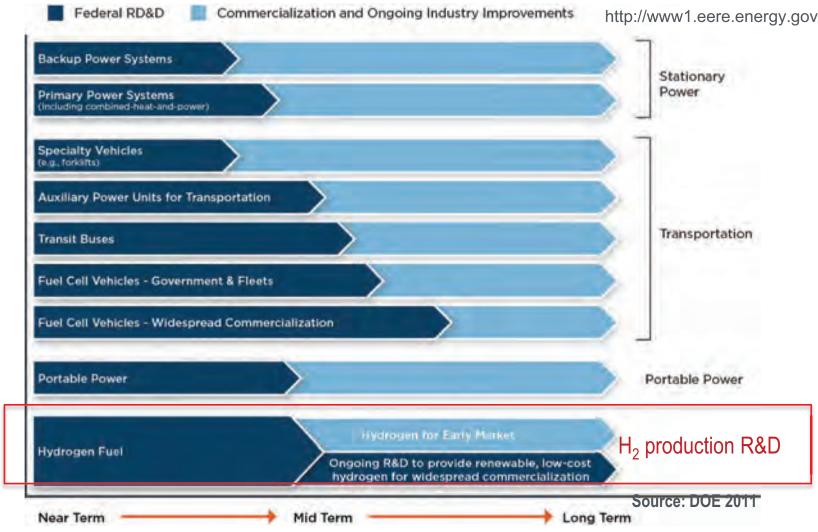


- ***1,000 fuel cell deployments in ~ 2 years***
- ***1 million hours of operation***

**IDIQ = indefinite delivery/indefinite quality*

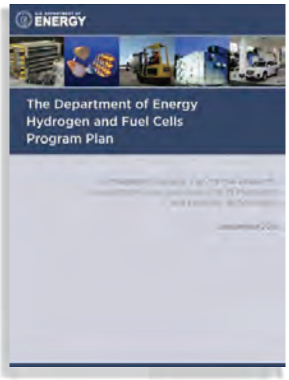
Fuel Cell Technologies Program Plan

- Fuel Cell Technologies (FCT) Program R&D has led to significant progress in early-markets
- Continued R&D focus on low-carbon H_2 production for near- to long-term markets is needed



Source: DOE 2011

http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/program_plan2011.pdf



The Department of Energy Hydrogen and Fuel Cells Program Plan

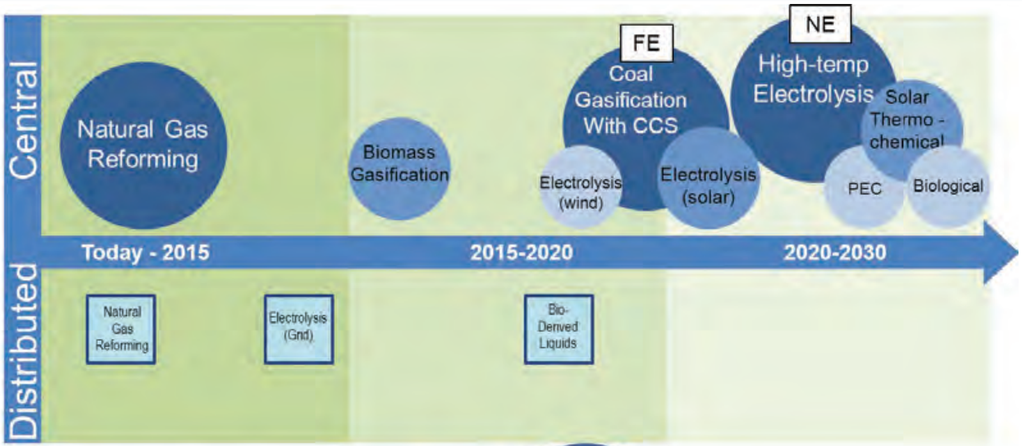
Update to the Hydrogen Posture Plan (2006)

Program efforts are planned to transition to industry as technologies reach commercial-readiness.

Released September 2011

DOE Portfolio of H_2 Production Technologies

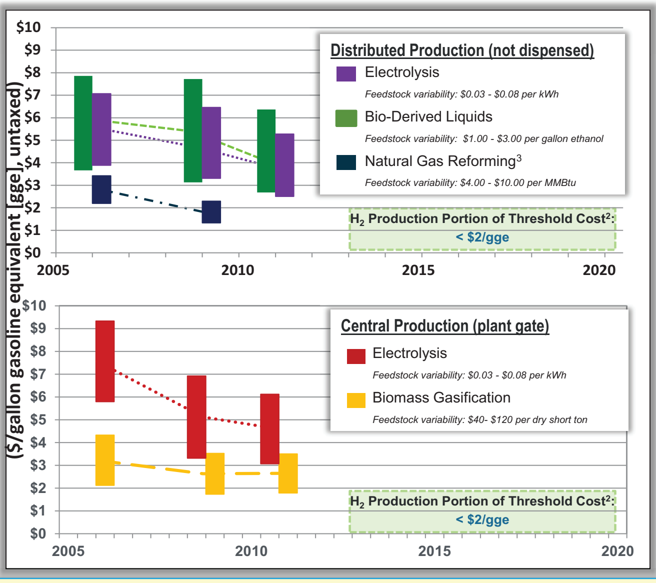
The EERE-Fuel Cell Technologies (FCT) Program uses independent analyses and pathway case studies to prioritize R&D in a range of central and distributed hydrogen production pathways, and to strives to identify synergies with DOE Offices of Nuclear Energy (NE), Fossil Energy (FE) and Science (SC) Offices (e.g., EFRCs and Solar Fuels Hub), and collaborations with industry, academia and the national laboratories. 0



FE, NE R&D efforts in DOE Offices of Fossil and Nuclear Energy, resp.

Production Cost Challenge

Projected High-Volume Cost of Hydrogen Production with Feedstock Sensitivities[1]



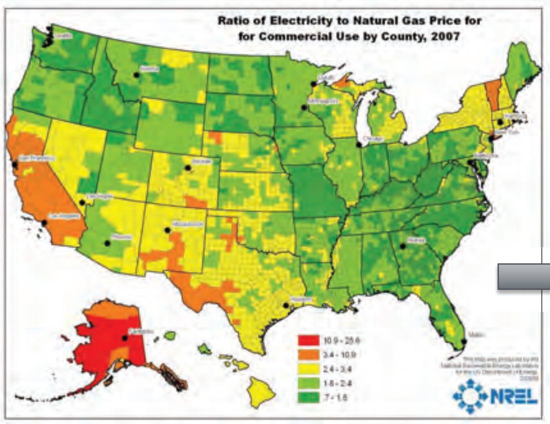
Among currently available pathways, only natural gas reforming meets H_2 cost threshold over a broad range of feedstock costs (at high volumes)

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 N^th^-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)

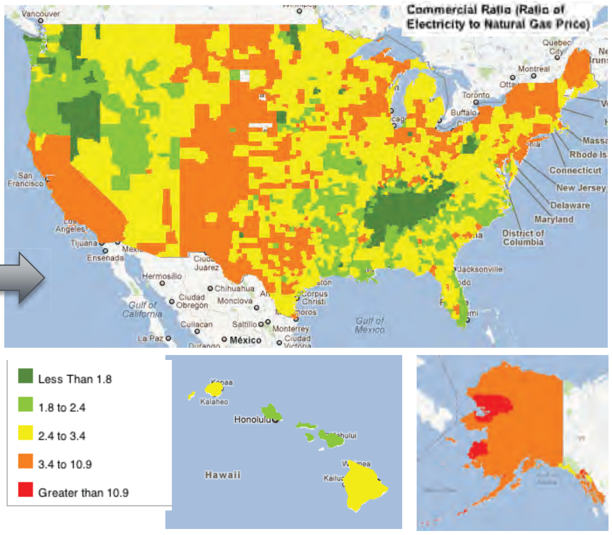
- **Natural gas reforming can bootstrap high-volume production for expanding near-term energy applications and bridge to longer-term low-carbon alternative pathways**
- **Continued coordination of fundamental and applied R&D with industry needs is essential to developing new, affordable pathways for producing low-carbon hydrogen for large-scale energy markets** 1

Spark-Spread Determines Regional Opportunities for DG from Natural Gas

2007



2010



Spark spread determines regions for favorable use of natural gas

Red/orange regions: High electricity cost, low natural gas cost- favorable for DG 2

Lower natural gas prices offer increased opportunities for CHP and distributed generation- current vs. 2007

Source: NREL

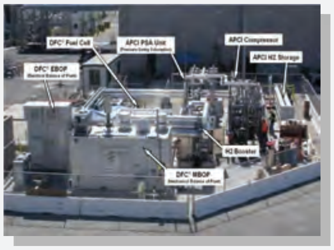
Tri-Generation of Heat, Hydrogen, and Power

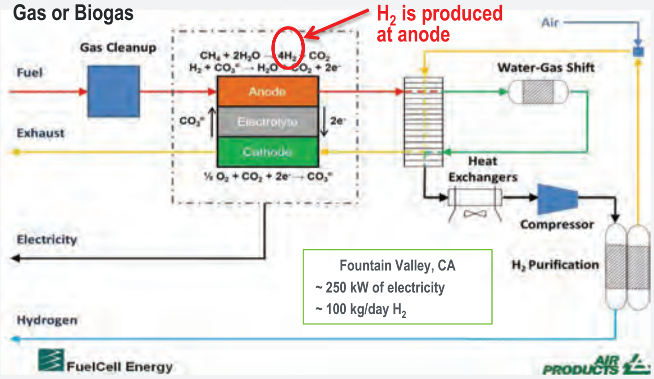
Potential Opportunity

Does a synergy exist between stationary and transportation sectors?

Demonstrated world's first Tri-generation station (54% efficiency – H_2 and power)

-Anaerobic digestion of municipal wastewater-



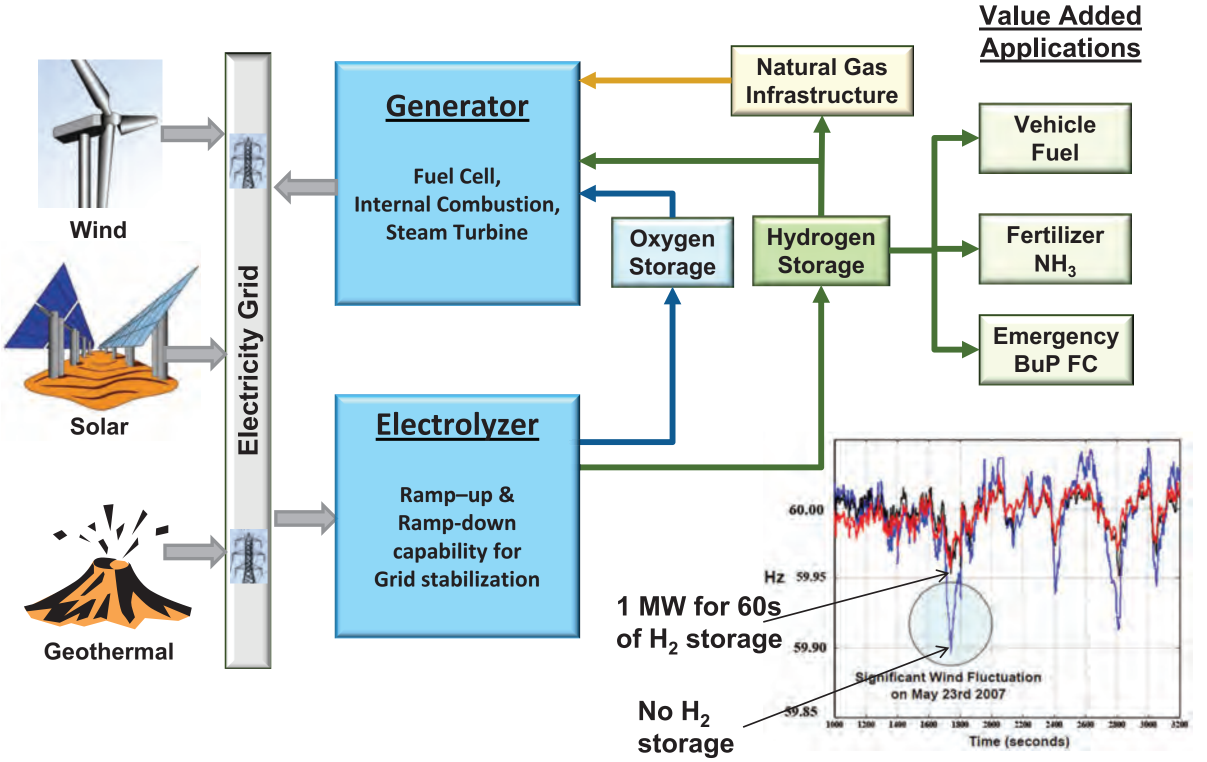


Fountain Valley, CA
~ 250 kW of electricity
~ 100 kg/day H_2

Is tri-generation a viable option for H_2 production:

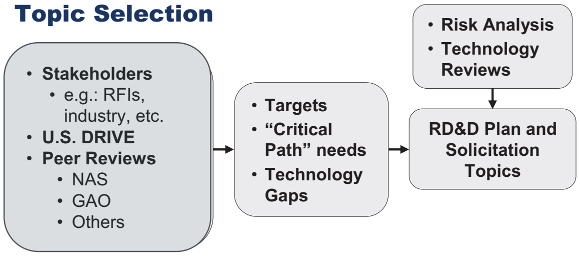
- Co-produce H_2, power, and heat for multiple applications?
- More efficient use of natural gas?
- Use a renewable resource in anaerobic digester gas?
- Use off-gas from other waste material processing (e.g., gasifiers)?
- Establish an early market infrastructure?

H_2 for Energy Storage



Methodology – Includes competitive review processes, peer reviews & risk analyses

Topic Selection



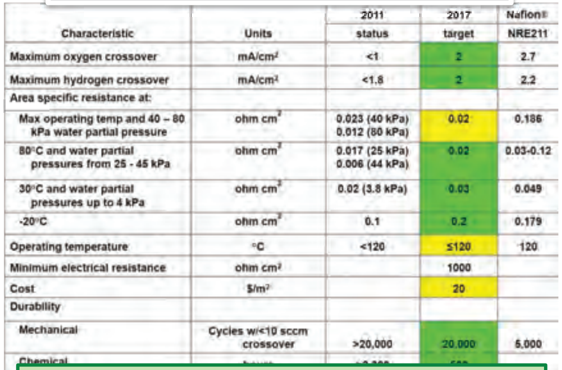
- **Stakeholders**
  - e.g.: RFIs, industry, etc.
- **U.S. DRIVE**
- **Peer Reviews**
  - NAS
  - GAO
  - Others

- **Targets**
- **"Critical Path" needs**
- **Technology Gaps**

- **Risk Analysis**
- **Technology Reviews**

RD&D Plan and Solicitation Topics

Example Fuel Cell Membrane Targets



Characteristic	Units	2011 status	2017 target	Nafion® NRE211
Maximum oxygen crossover	mA/cm²	<1	2	2.7
Maximum hydrogen crossover	mA/cm²	<1.8	2	2.2
Area specific resistance at:				
Max operating temp and 40 – 80 kPa water partial pressure	ohm cm²	0.023 (40 kPa) 0.012 (80 kPa)	0.02	0.186
80°C and water partial pressures from 25 - 45 kPa	ohm cm²	0.017 (25 kPa) 0.006 (44 kPa)	0.02	0.03-0.12
30°C and water partial pressures up to 4 kPa	ohm cm²	0.02 (3.8 kPa)	0.03	0.049
-20°C	ohm cm²	0.1	0.2	0.179
Operating temperature	°C	<120	≤120	120
Minimum electrical resistance	ohm cm²		1000	
Cost	$/m²		20	
Durability				
Mechanical	Cycles w/<10 sccm crossover	>20,000	20,000	5,000
Chemical				

Technical targets help guide go/no-go decisions.

Project & Program Review Processes

- Annual Merit Review & Peer Evaluation meetings (EE, NE, FE, SC)
- Tech Team reviews (monthly)
- Other peer reviews- National Academies, GAO, etc.
- DOE quarterly reviews and progress reports

Project Number	Project Title *PI Name & Organization*	Final Score	Continue	Discontinue	Other	Summary Comment
123	Fluoroalkyl-Phosphonic-Acid-Based Proton Conductors *Xxx University*	2.7		X		Progress was made in molecular dynamics modeling of model compounds, but the membranes synthesized failed in testing and did not meet the conductivity targets. The project will not be continued.

Over $19M saved in the last 3 years through go/no-go decisions

Reviewer comments for projects posted online annually. Projects discontinued/ work scope altered based on performance & likelihood of meeting goals.

Go / No-go Decisions & Independent Assessments

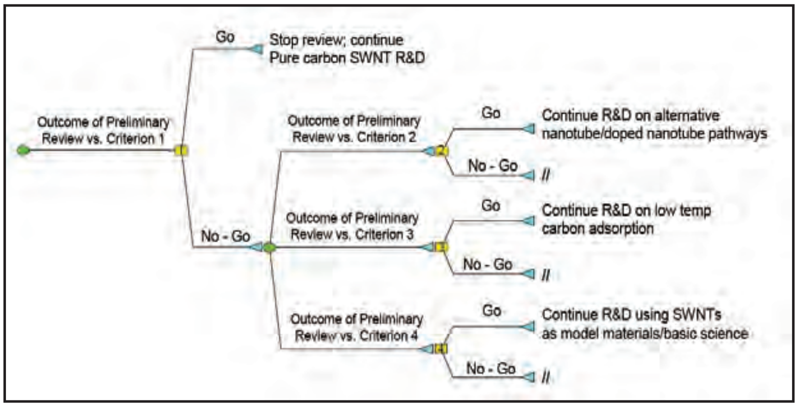
"Go / No-go" decisions are used in downselecting certain research pathways to focus on the most promising areas. They are defined by performance-based technical milestones and quantitative metrics. Expert Panels are convened for independent assessments.

A "no-go" decision

- May indicate that further advances in basic science are needed
- May eliminate an entire technology pathway

Key examples

- Single-walled Carbon Nanotubes — "no-go"
- Thermochemical Hydrogen Production — three cycles selected out of 350
- Sodium Borohydride for On-Board Vehicular Hydrogen Storage — "no-go"
- On-board Fuel Processing — "no-go"



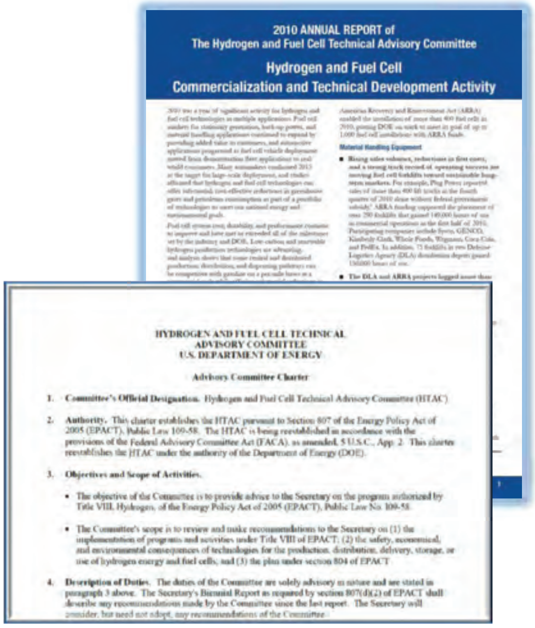
The decision tree used by the Program in the process of down-selecting pure carbon single-walled nanotubes (SWNTs) for hydrogen storage.

As a result of the first no-go decision shown on the left side of the figure, funding was redirected to the areas shown on the right side of the figure.

"Go/No-Go Decision: Pure, Undoped Single-Walled Carbon Nanotubes for Vehicular Hydrogen Storage," U.S. Department of Energy, October 2006, www.hydrogen.energy.gov/pdfs/go_no_go_nanotubes.pdf.

The HTAC Charter

- HTAC was established under ***Section 807 of the Energy Policy Act of 2005*** to provide technical and programmatic advice to the Energy Secretary on DOE's hydrogen research, development, and demonstration efforts.
- Committee's scope is to review and make recommendations to the Secretary on:
  - Implementation of programs and activities under Title VIII of EPACT;
  - Safety, economical, and environmental consequences of technologies for the production, distribution, delivery, storage, or use of hydrogen energy and fuel cells; and
  - Plan under section 804 of EPACT.



2010 ANNUAL REPORT of
The Hydrogen and Fuel Cell Technical Advisory Committee

Hydrogen and Fuel Cell
Commercialization and Technical Development Activity

Material Handling Equipment

HYDROGEN AND FUEL CELL TECHNICAL
ADVISORY COMMITTEE
U.S. DEPARTMENT OF ENERGY

Advisory Committee Charter

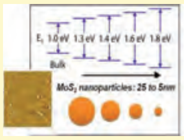
1. **Committee's Official Designation.** Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)
2. **Authority.** This charter establishes the HTAC pursuant to Section 807 of the Energy Policy Act of 2005 (EPACT), Public Law 109-58. The HTAC is being reestablished in accordance with the provisions of the Federal Advisory Committee Act (FACA), as amended, 5 U.S.C., App. 2. This charter reestablishes the HTAC under the authority of the Department of Energy (DOE).
3. **Objectives and Scope of Activities.**
   - The objective of the Committee is to provide advice to the Secretary on the program authorized by Title VIII, Hydrogen, of the Energy Policy Act of 2005 (EPACT), Public Law No. 109-58.
   - The Committee's scope is to review and make recommendations to the Secretary on (1) the implementation of programs and activities under Title VIII of EPACT; (2) the safety, economical, and environmental consequences of technologies for the production, distribution, delivery, storage, or use of hydrogen energy and fuel cells; and (3) the plan under section 804 of EPACT.
4. **Description of Duties.** The duties of the Committee are solely advisory in nature and are stated in paragraph 3 above. The Secretary's Biennial Report as required by section 807(d)(2) of EPACT shall describe any recommendations made by the Committee since the last report. The Secretary will consider, but need not adopt, any recommendations of the Committee.

2012 H_2 Production Expert Panel

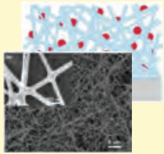
A Subcommittee of HTAC* formed with DOE EERE-FCT Support, bringing together visionary leaders from industry, academia and the national laboratories, to:

- *Evaluate current status of hydrogen production technologies*
- *Identify remaining challenges in near- and long- term production pathways, and prioritize R&D needs*
- *Strategize how to best leverage R&D among DOE Offices and with other agencies*
- *Provide recommendations to HTAC to enable a path forward for the widespread production of affordable low carbon hydrogen.*

EERE/EFRC Collaboration on PEC

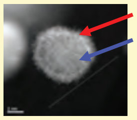


Bandgap tailoring

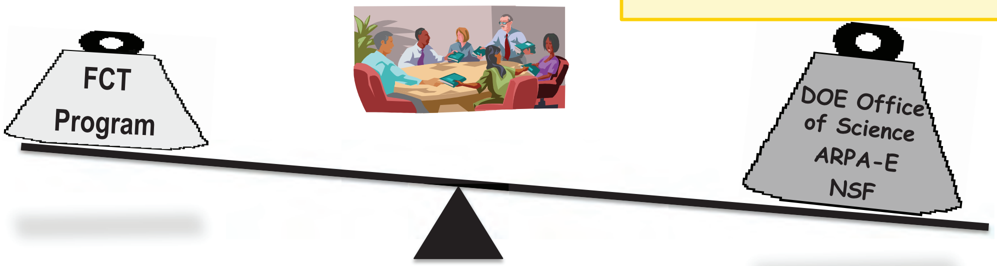


Nano-catalyst support scaffold (Stanford)

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

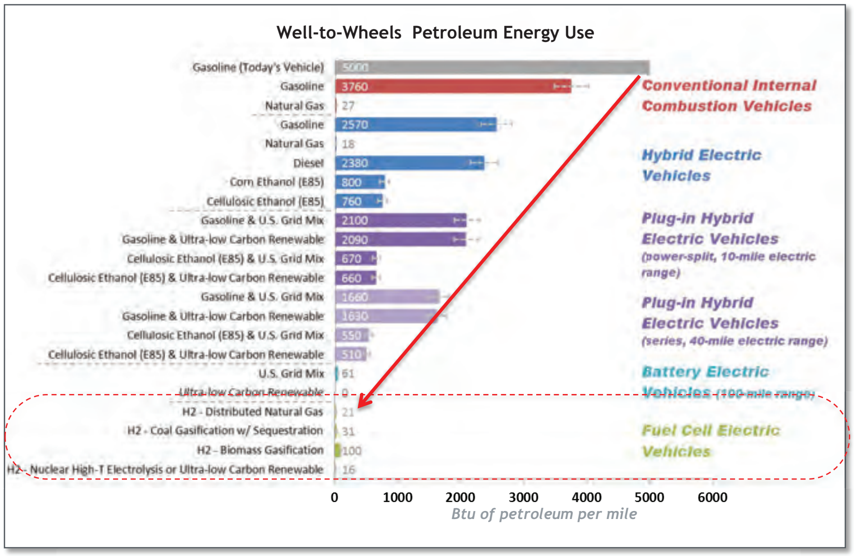
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BACKUP

Well-to-Wheels Petroleum Analysis

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

Analysis by Argonne National Lab, DOE Vehicle Technologies Program, and FCT Program shows benefits from a portfolio of options.



H_2 from Natural Gas

FCEVs fueled by H_2 from distributed natural gas can almost completely eliminate petroleum use.

Notes:
For a projected state of technologies in 2035-2045. Ultra-low carbon renewable electricity includes wind, solar, etc. Does not include the life-cycle effects of vehicle manufacturing and infrastructure construction/decommissioning.
Analysis & Assumptions at: http://hydrogen.energy.gov/pdfs/10001_well_to_wheels_gge_petroleum_use.pdf

EERE Budget Appropriations and Request

Funding (*$ in thousands)*

EERE Program	FY 2010 Appropriation	FY 2011 Allocation	FY 2012 Appropriation	FY 2013 Request
Hydrogen & Fuel Cell Technologies	170,297	95,847	103,624	80,000
Biomass & Biorefinery Systems R&D	216,225	179,979	199,276	270,000
Solar Energy	243,396	259,556	288951	310,000
Wind Energy	79,011	78,834	93,254	95,000
Geothermal Technologies	43,120	36,992	37,862	65,000
Water Power	48,669	29,201	58,787	20,000
Vehicle Technologies	304,223	293,151	328,807	420,000
Building Technologies	219,046	207,310	219,204	310,000
Advanced Manufacturing	94,270	105,899	115,580	290,000
Federal Energy Management Program	32,000	30,402	29,891	32,000
Facilities & Infrastructure	19,000	51,000	26,311	26,400
Weatherization and Intergovernmental	270,000	231,300	128,000	195,000
Program Direction	140,000	170,000	165,000	164,700
Strategic Programs	45,000	32,000	25,000	58,900
Adjustments	292,135	(29,750)	(9,909)	(69,667)
Total	$2,216,392	$1,771,721	$1,809,638	$2,267,333

FY 13 House Mark (HFCT) $82M

FY 13 Senate Mark (HFCT) $104 M

DOE Hydrogen Budget

Funding *($ in thousands)*

	FY 2007 Approp.	FY 2008 Approp.	FY 2009 Approp.	FY 2010 Approp.	FY 2011 Allocation	FY 2012 Approp.	FY 2013 Request
EERE Hydrogen & Fuel Cells	189,511	206,241	195,865	170,297	95,847	101,087	77,850
Fossil Energy (FE)	21,513	14,891	20,151	13,970	11,394	0	0
Nuclear Energy (NE)	18,855	9,668	7,340	5,000	2,800	0	0
Science (SC)	36,388	36,483	38,284	38,053	34,611	~34,611	TBD
DOE TOTAL	266,267	267,283	261,640	227,320	144,652	~135,698	TBD

EERE FY 13 House Mark: $82 M

EERE FY 13 Senate Mark: $104 M

SECA House & Senate Mark: $25 M

Notes
Nuclear Energy: In 2010 and 2011, development of HTSE at the Idaho National Laboratory (INL) continued with funding from the NGNP project. Several industry partners now have stack technologies for high temperature steam electrolysis in development. After demonstration of pressurized HTSE stack operation in FY 2012 by INL, the technology readiness is expected to be sufficiently advanced (TRL5) to allow for further development by industry.
EERE: FY 2012 appropriation and FY 2013 request exclude the estimated SBIR/STTR funding.

EERE H_2 & Fuel Cells Budgets

Appropriations (FY 10 – FY 12) and Budget Request (FY 13)
Hydrogen and Fuel Cell Technologies

Funding *($ in thousands)*				
Key Activity	**FY 2010 Appropriation**	**FY 2011 Allocation**	**FY 2012 Appropriation**	**FY 2013 Request**
Fuel Cell Systems R&D	**75,609**	**41,916**	**44,812**	**38,000**
Hydrogen Fuel R&D	**45,750**	**32,122**	**34,812**	**27,000**
Technology Validation	**13,005**	**8,988**	**9,000**	**5,000**
Market Transformation	**15,005**	**0**	**3,000**	**0**
Safety, Codes & Standards	**8,653**	**6,901**	**7,000**	**5,000**
Education	**2,000**	**0**	**0**	**0**
Systems Analysis	**5,408**	**3,000**	**3,000**	**3,000**
Manufacturing R&D	**4,867**	**2,920**	**2,000**	**2,000**
Total	**$170,297**	**$95,847**	**$103,624**	**$80,000**

FY 13 House Mark $82 M

FY 13 Senate Mark $104 M

Notes: Hydrogen Fuel R&D includes Hydrogen Production & Delivery R&D and Hydrogen Storage R&D. FY11, FY12 include SBIR/STTR funds to be transferred to the Science Appropriation; prior years exclude this funding

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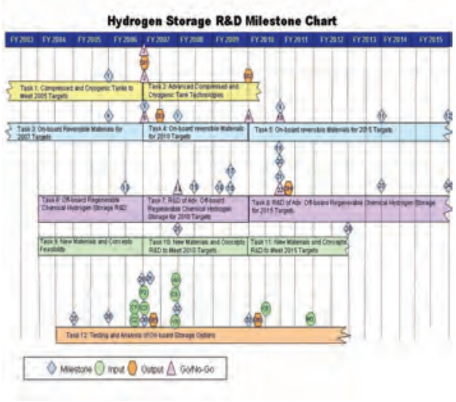
Subprogram Milestones and Targets - Examples

Each subprogram has detailed milestones, inputs, outputs, go-no go decision points and technical targets



Update of Multiyear RD&D Plan in process

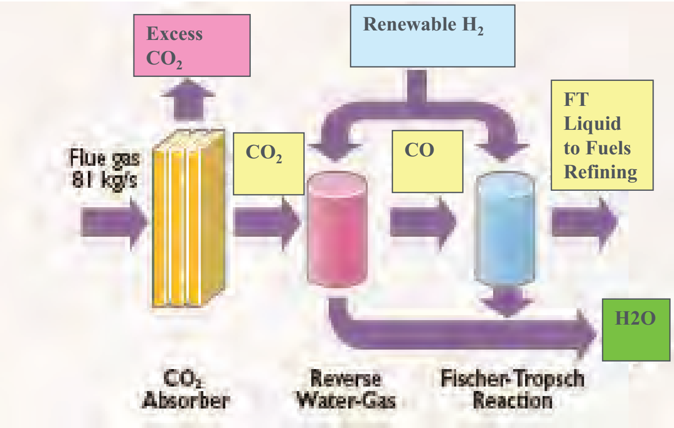
Example- Target Table for Electrocatalysts

Electrocatalysts for Transportation Applications	Status[a]	Targets[b]
	2011	**2017**
Platinum group metal (PGM) total content (both electrodes)	**0.19 g/kW**	**0.125 g/kW**
PGM Total Loading	**0.15 mg/cm^2**	**0.125 mg/cm^2**
Loss in catalytic (mass) activity[c]	**<40%**	**<40% loss of initial**
Catalyst support loss[d]	**<10% mass loss**	**< 10% mass loss**
Mass activity[e]	**0.24 A/mg Pt in MEA >0.44 A/mg Pt new alloy in RDE**	**0.44 A/mg PGM**
Activity per volume of supported catalyst (non-PGM)[f]	**60 A/cm^3 (measured) 160 A/cm^3 (extrapolated)**	**>300 A/cm^3**

[a] single cell status – will require scale-up
[b] preliminary targets – approval pending
[c] after 30,000 cycles from 0.6 – 1.0 V; after 400 hours at 1.2 V
[d] after 400 hours at 1.2 V
[e] baseline @ 900mV$_{\text{IR-free}}$
[f] baseline @ 800mV$_{\text{IR-free}}$

H	= High (significant challenge)	**M**	= Medium
M/H	= Medium/High	**L**	= Low (minimal challenge)

Hydrogen has the potential to reduce CO_2 and produce renewable liquid fuel if process cost can be reduced.



Source: Dr. Robert E. Uhrig, "Implementing the "Hydrogen Economy with Synfuels, 2007.

Preliminary Capital and Operating Cost

	FT from CO2 (Flue Gas) and Renewable Hydrogen	
FT plant	**470 M$**	
CO_2 Absorber & Reverse Water Gas Shift	**400 M$**	*
Electrolysis-H_2	**1,800 M$**	*
Total Capital	**2,670 M$**	
Offsite & Contingency	**2,480 M$**	*
Total Investment	**5,150 M$**	
Levelized Capital	**730 M$/yr**	
O&M (2%)	**100 M$/yr**	
Total Annual Cost	**830 M$/yr**	
Cost of FT Crude	**$3/gal**	
Cost of Distillate (Diesel and Jet Fuel)	**$7/gal**	

Notes:* Potential areas for cost reduction.

Assumptions:

- **Plant capacity is ~17,000 BPD.**
- **Power is assumed to be zero because supplied from curtailed wind.**

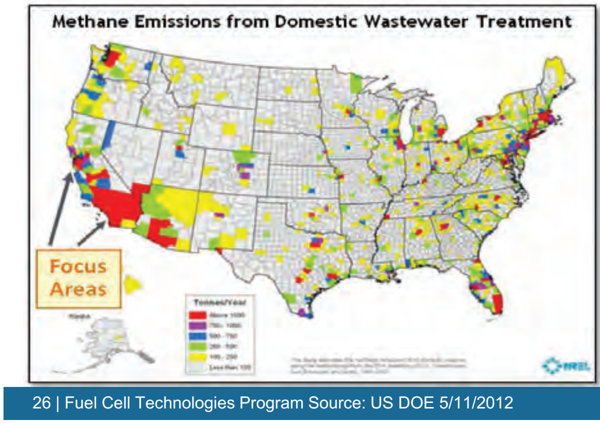
Biogas as an Early Source of Renewable Hydrogen and Power

- ***The majority of biogas resources are situated near large urban centers—ideally located near the major demand centers for hydrogen generation for hydrogen fuel cell vehicles (FCEVs) and power generation from stationary fuel cells.***
- ***Hydrogen can be produced from this renewable resource using existing steam-methane-reforming technology.***

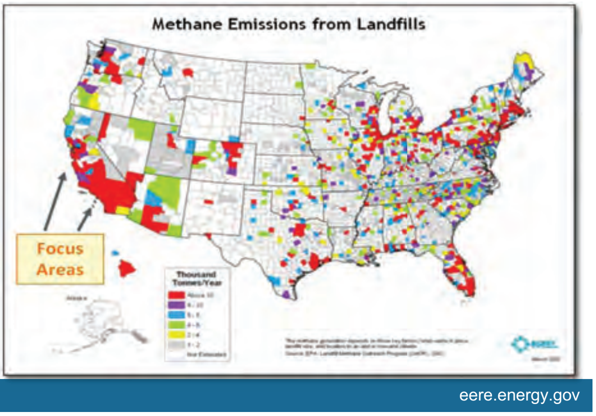
U.S. biogas resource has capacity to produce ~5 GW of power at 50% electrical efficiency.

Hydrogen generated from biogas can fuel ~8-13M FCEVs/day.

- 500,000 MT per year of methane is available from wastewater treatment plants in the U.S.
- ~50% of this resource could provide **~340,000 kg/day** of hydrogen.

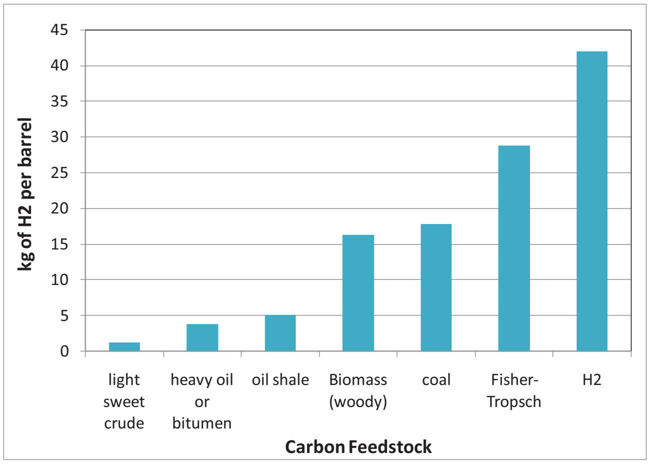

Methane Emissions from Domestic Wastewater Treatment

- 12.4 million MT per year of methane is available from landfills in the U.S.
- ~50% of this resource could provide **~8 million kg/day** of hydrogen.


Methane Emissions from Landfills

Hydrogen Requirements for Carbon Feedstocks also Adds to Demand

Hydrogen requirements for processing of carbon feedstocks to produce liquids fuels[1]



[1]"Review of the Potential of Nuclear Hydrogen for Addressing Energy Security and Climate Change," James E.O'Brien, *Nuclear Technology*, VOL. 178 nr 1, pp 55-65, April 2012.

Hydrogen Demand for Biomass Upgrading

Production of pyrolysis oil from corn stover

- Annual corn stover production is ~400 million tons and represents ~40% of the biomass resource in the U.S.[1]
- Thermal conversion of ~2000 metric tons/d of corn stover yields ~3,500 bbls /day of pyrolysis oil.[2]
- Upgrading and stabilization of pyrolysis oil to naphtha and diesel products requires ~49,000 kg/d (~18 million kg/yr.) of hydrogen.
- Thermal conversion of the corn stover biomass to upgraded pyrolysis oil would require ~9-10 million metric tons/yr.

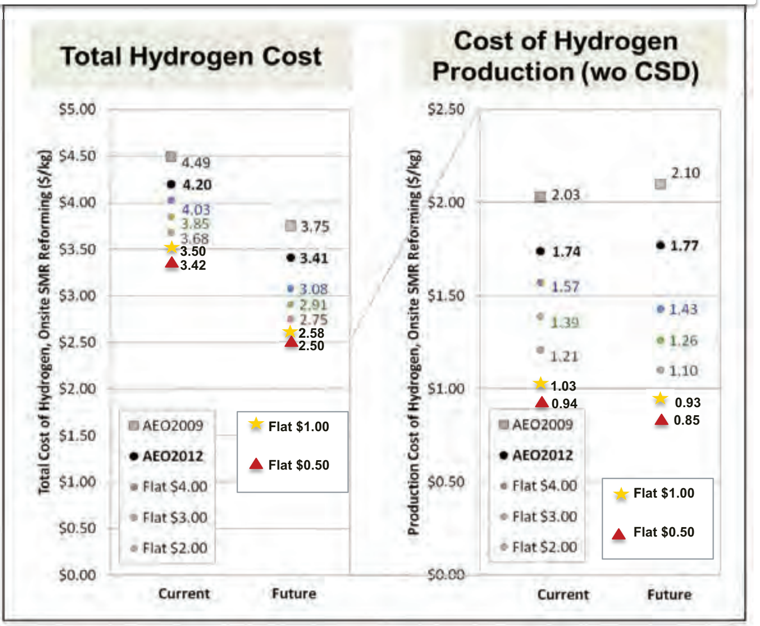
Notes:
[1]Amount of corn stover was obtained from second Billion Ton Study.
[2]Source for the hydrogen demand was an NREL study Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels by Mark M. Wright, Justinus A. Satrio, and Robert C. Brown Iowa State University Daren E. Daugaard ConocoPhillips David D. Hsu NREL

NG and Hydrogen Cost Analysis

Natural gas price projections have declined in recent years and the corresponding cost of hydrogen*, also declines**

Distributed Hydrogen Production from NG SMR

- Total hydrogen cost (production plus station compression, storage and compression [CSD]) and production cost for Current and Future forecourt SMR stations
- Current Case: Startup year is 2010; Station life is 2010-2030
- Future Case: Startup year is 2020; Station life is 2020-2040
- The cost of natural gas ($/MMBtu) is only a fraction of the total cost of hydrogen
- Difference between the two charts is the cost of CSD.



*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)

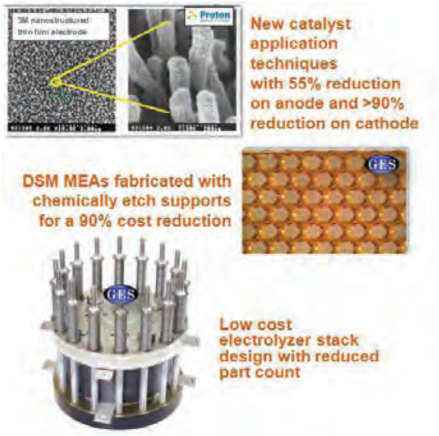
Accomplishments & Innovations

- The projected high-volume cost of fuel cells is now estimated at $49/kW in 2011, a more than 80% reduction since 2002 and >30% reduction since 2008. Key accomplishments include reducing platinum group metal content from >1 g/kW to <0.2 g/kW, demonstrating a >5x improvement in power per gram of Pt, and more than doubled the durability (to 2,500 hours, or ~75,000 miles) of transportation fuel cells since 2006.
- Research in both distributed and central production have resulted in continued progress in all pathways including electrolysis, bio-derived liquids, natural gas reforming, and biomass gasification with some pathways already within the recently completed hydrogen threshold cost target of $2-4/gge.
- The Technology Validation Learning Demonstration is coming to a close in 2012. This project has provided valuable data on hydrogen fuel cell electric vehicles and infrastructure. Over 180 fuel cell electric vehicles and 25 stations were demonstrated and ~3.6 million miles traveled. The vehicles were driven >146,000 hours. ~2,500 hours (nearly 75K miles) durability was demonstrated along with ~5 minute refueling time for 4 kg of hydrogen.
- Hydrogen fuel cell buses have demonstrated a 42% to 139% better fuel economy compared to diesel & CNG buses.
- Hydrogen storage tanks can achieve >250 mile range and a 430 mile range has been validated on FCEVs.

DOE Investments have Resulted in Commercial Progress

DOE programs have reduced cost of commercial H_2 production technologies

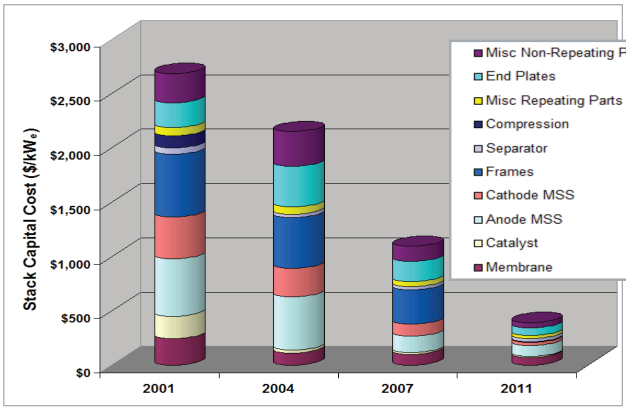
- Reduced electrolyzer stack costs by greater than 80% since 2001 through component optimization and manufacturing innovations (Proton Onsite, Giner, Inc.)



New catalyst application techniques with 55% reduction on anode and >90% reduction on cathode

DSM MEAs fabricated with chemically etch supports for a 90% cost reduction

Low cost electrolyzer stack design with reduced part count

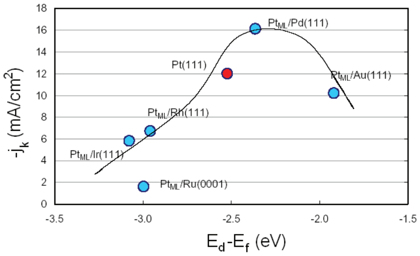


- Fundamental and applied R&D have been successfully leveraged by industry to advance hydrogen and fuel cell technologies
  - –For example, fundamental nano-structured catalyst work has helped lead to significant cost reductions in PEM fuel cells and PEM electrolyers for hydrogen production (ANL, 3M)

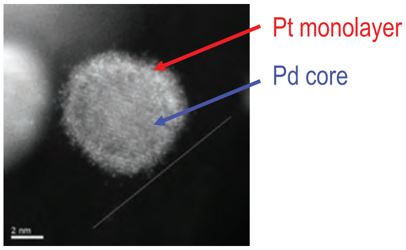
Pt/Pd Core-Shell Catalysts

Fundamental research has demonstrated high activity of Pt monolayer catalysts, leading to development of practical core-shell catalysts through applied R&D

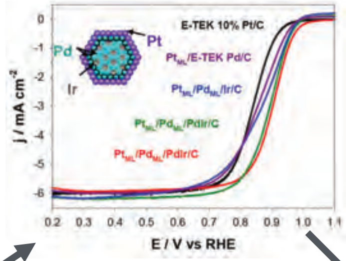
Fundamental Science → *Applied R&D*



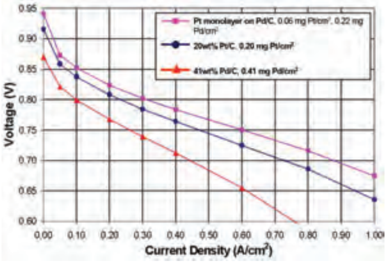
High activity of Pt monolayer surfaces was demonstrated on model (single-crystal) surfaces. Substrate metal modifies Pt electronic structure, allowing tuning of catalytic activity and durability.



Demonstration of Pt monolayer on a Pd core – a promising high activity, high durability, low-loading PGM catalyst.



Addition of other metals to core, along with interlayers between shell and core, further enhance core-shell activity and durability.



Scale-up to gram-level quantities of core-shell catalysts in EERE-funded partnership with Cabot, as well as external CRADAs.

Adzic *et al.*, BNL

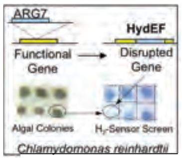
Advancements in Biological Hydrogen Production

National Renewable Energy Laboratories

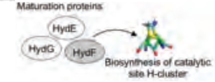
O_2 sensitivity of the hydrogenase (H_2ase) catalyst prevents sustained H_2 photo-production and results in low light conversion efficiencies under anaerobic conditions

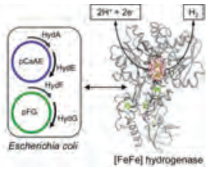
Office of Science-funded research (Basic)

Goal: understand the growth factors and signal transduction pathways that regulate transcription of the H_2ase genes in green algae



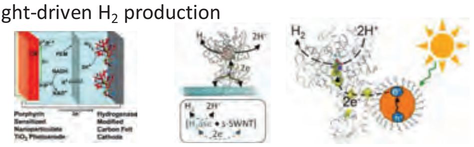
HYDEF mutant in *C. reinhardtii* cannot assemble [FeFe]-H_2ase catalytic site





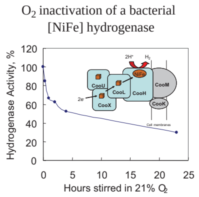
Over-expression of maturases HydE, F and G and structural protein HydA to produce active [FeFe]-H_2ases in the bacterium, *E. coli*

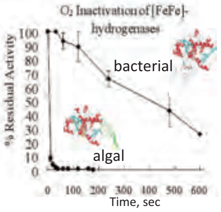
Goal: understand molecular assembly and function of H_2ases in artificial photosynthetic systems for light-driven H_2 production



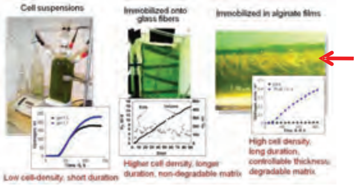
EERE-funded research (Applied R&D)

Goal: express a more O_2-tolerant bacterial H_2ase in oxygenic photosynthetic organisms (algae or cyanobacteria) to function under *aerobic* conditions





Goal: optimize sustained *anaerobic* H_2 production and use it to examine other limiting factors to guide development aerobic H_2 Production to meet targets



Yields H_2 with a conversion efficiency of ~1% under aerobic conditions and low fluorescent light intensity

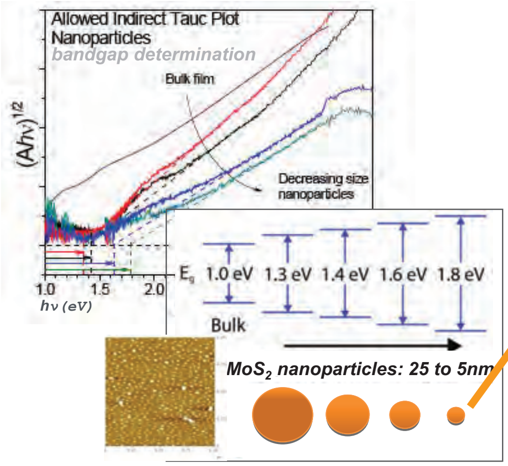
NREL

Novel Nano-Catalyst System for Solar Hydrogen Production
Coordinated SC-EFRC and EE-FCT work at Stanford/U-Louisville/NREL

Discovering new MoS_2 nano-catalysts, and developing novel macro-structures for integration into practical photoelectrochemical (PEC) hydrogen production devices

Fundamental Science:

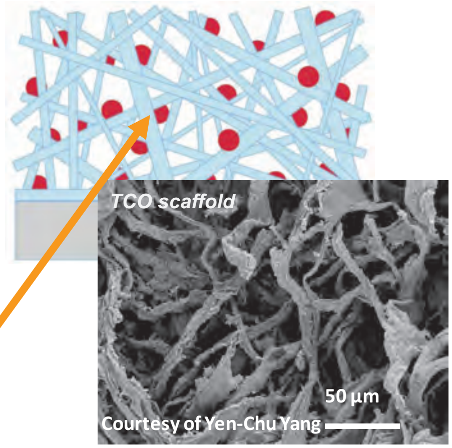
Based on fundamental principles of quantum confinement, nanoparticle MoS_2 catalysts exhibit bandgap enlargement from 1.2 eV (bulk) to ~1.8 eV when diameter is reduced to ~5 nm.



Bandgap blueshift in 5 nm MoS_2 nanoparticles sensitizes catalyst to efficiently absorb light in the solar spectrum

Applied R&D:

A macroporous scaffold consisting of a transparent conducting oxide (TCO) is being developed upon which the MoS_2 nanoparticles can be vertically integrated for support, confinement and electronic contact.



Scaffold is enabling technology for development of MoS_2 photoelectrodes for effective solar H_2 production

STANFORD UNIVERSITY

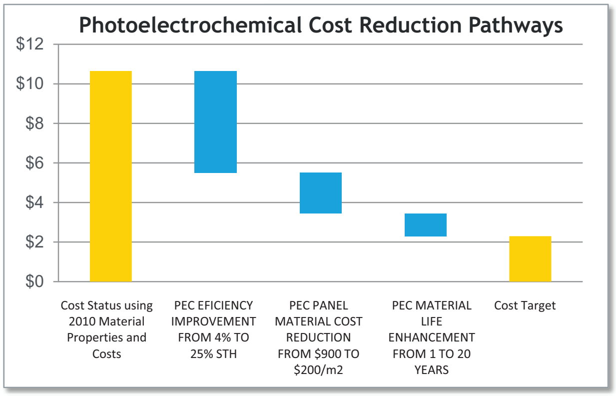
LOUISVILLE

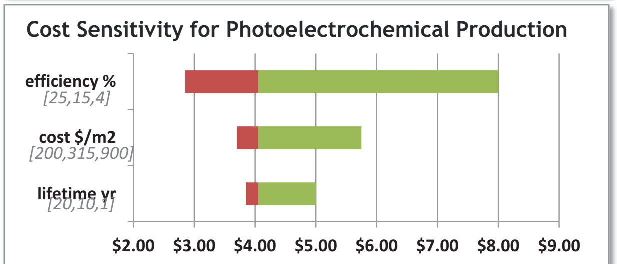
NREL

Source: T. Jaramillo, et al. *Science 2007, 317, 100122;* Y. Aoki, J. Huang, T. Kunitake, *J. Mater. Chem., 2006, 16, 292-297*

Cost Reduction Roadmap for H_2 Production
Example — Photoelectrochemical Production

Potential areas for cost reduction guide R&D activities





$/kg H2 cost sensitivities for [long-, mid-, near-term] materials targets (based on DTI PEC Technoeconomic Boundary Level Analysis: Type 4 System)

MATERIAL EFFICIENCY: **Increase PEC efficiency from 4% (baseline) to 25%.**

Focus on novel integrated thin film device structures (e.g., with metal oxides) with multi-junction absorber layers for 1.8-2.2 V and enhanced surface catalysis for efficiency enhancements toward the 25% target

MATERIAL COST: **Decrease PEC panel material cost from $900/m² to $200/m².**

Focus on material and processing/fabrication cost reductions, e.g. breakthrough self-assembling semiconductor synthesis approaches (instead of vapor deposition, etc.)

MATERIAL LIFETIME: **Increase life from 1 to 20 yrs.**

Focus on advanced surface modification strategies to enhance catalysis and mitigate corrosion of the crystalline material systems currently capable of >18% solar-to-hydrogen conversion

NEW IDEAS: **Disruptive technologies incorporating nano-structured semiconductor, catalyst and membrane components with the potential for high efficiency and durability using low-cost synthesis routes (e.g., work with EFRC/Solar Hub on approaches such as nanoparticle MoS_2 in porous scaffold)**