Workshop on Electrolysis Production of Hydrogen From Wind and Hydropower

September 9-10, 2003 • Washington, DC

WORKSHOP PROCEEDINGS

Sponsored by

U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Hydrogen, Fuel Cells, and Infrastructure Technologies Program
and
Wind and Hydropower Technologies Program

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Introduction

Wind and hydropower technologies are currently being evaluated in the U.S. and abroad as electricity sources that could enable production of large quantities of low-cost renewable hydrogen for use in transportation and distributed power applications. These domestic, renewable power resources offer the potential to produce electricity at some of the lowest costs currently available for new power generation facilities. Low-cost renewable power can potentially enable cost-effective production of hydrogen via water electrolysis – a hydrogen production route that would expand domestic energy supply options and reduce demand for fossil fuel while avoiding emissions.

The co-production of electricity and hydrogen from wind and hydropower facilities offers some exciting prospects for optimizing electrolysis and power system efficiencies and lowering system costs. Coupling wind and hydropower turbines to low-cost electrolyzers can potentially:

- reduce the cost of system components by minimizing redundant systems (e.g., use of the wind turbine's controller and power electronics system to operate the electrolyzer, eliminating the need for these costly systems in the electrolyzer)
- provide additional incentives and synergies for co-located wind, hydropower, and hydrogen production facilities (e.g., to expand options for utilizing variable resources)
- improve electrical power system dispatchability and balance transmission loads
- provide options for optimizing outputs of products (electricity and/or hydrogen) based on site-specific energy demand and cost factors.
- provide innovative opportunities for off-peak energy storage (e.g., use of a wind turbine tower to store hydrogen or hydro pumped storage systems).

There are a variety of uncertainties concerning the technical and economic feasibility of central and distributed production of hydrogen from wind and/or hydropower. Chief among these are 1) the capability to produce electricity at a cost that would enable bulk production of cost-competitive hydrogen (currently estimated at 2.0-3.5¢/kWh); 2) the need to lower electrolyzer capital cost and improve hydrogen production efficiency; 3) the need for optimal system configuration designs; and 4) the need to resolve power system integration issues at local, regional and national levels.

Workshop Purpose

To further explore the potential for cost-effective electrolysis production of hydrogen from wind and/or hydropower, the U.S. Department of Energy (DOE) hosted a workshop of key stakeholders from the private sector and research community. The workshop had three key goals:

1) To begin a dialogue among representatives from the wind turbine, hydropower, and electrolysis industries on key opportunities and potential technology synergies.

2) To review and gather industry feedback on current modeling and analysis efforts funded by DOE on the potential for co-production of electricity and hydrogen from wind and hydropower.

3) To get industry input on key challenges to electrolysis production of hydrogen from wind and hydropower and the research and development (or other) activities that are needed to address these challenges.

Workshop Format

The workshop agenda, shown in Appendix A, was structured to provide time for both presentations and discussion among the participants. Background presentations were delivered by DOE's Hydrogen & Fuel Cells and Wind & Hydropower programs, as well as by industry participants.[1] A strawman "Vision" for evolutionary development of hydrogen production from wind and hydropower (developed by DOE) was presented to the group and comments were received. The workshop participants were briefed on the status of DOE's wind-hydrogen modeling and analysis efforts by researchers at the National Renewable Energy Laboratory (NREL). The participants offered feedback on modeling assumptions, methodology and next steps. The final phase of the workshop involved two facilitated sessions that gathered input from participants on the grand challenges to electrolysis production of hydrogen from wind and hydropower and the R&D (or other) activities needed to overcome these challenges. The workshop was attended by 53 participants representing wind turbine manufacturers, electrolyzer manufacturers, hydropower generation facilities, utility companies, research institutes, national laboratories, trade and public interest associations, consulting research firms, and DOE, as shown in Appendix B.

Workshop Results

The following sections summarize the workshop's discussion sessions, with a focus on the comments and feedback of workshop participants.

Draft Vision and Comments

[1] **Presentations can be viewed and downloaded at** **http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/wkshop-wind-hydro.htlm**

Figure 1 presents a draft vision for the "Role of Wind and Hydropower in Hydrogen Production." This vision was developed for the workshop by staff in DOE's Wind & Hydropower Technologies Program and DOE's Hydrogen, Fuel Cells & Infrastructure Technologies Program as a strawman for consideration and further refinement. Its key purpose is to help clarify the expectations for these two renewable hydrogen pathways by envisioning a realistic evolutionary path for development of hydrogen production from wind and hydropower, and how the technology would fit into the nation's energy infrastructure (including production, distribution and end-use applications in the near, mid, and long term). As described in Figure 1, during the near-term (now through 2015), smaller-scale stand-alone and grid-connected systems would predominate, serving local transportation fleets and emerging distributed power applications. By 2015, several larger-scale electrolysis facilities supplying bulk hydrogen via an emerging pipeline, truck, or rail distribution infrastructure would be built to serve growing hydrogen markets near major demand centers. Off-shore wind, off-peak hydro, and co-located wind and hydro would be capable of marketing both hydrogen and electricity, in whatever combination optimizes demand and economic conditions. In the longer term, 2030 and beyond, additional large-scale, grid-connected electrolysis facilities would be supported by major pipeline and electric power system projects. These facilities are integrated into the grid system with other generation resources as controllable load assets, and provide synergies with other energy technologies, such as electrolysis-produced oxygen for oxygen-blown gasification and wastewater treatment, and hydrogen utilization for ammonia production. The vision shown here should be considered a "work in progress." Further refinements will be made as more is learned about the technical possibilities and timeline for these technologies.

Modeling Activities and Comments

This session focused on two DOE-supported modeling efforts underway at the National Renewable Energy Laboratory (NREL) to evaluate the national potential for co

production of electricity and hydrogen from wind and hydropower (current focus is on wind power). In the first analysis project, presented by Walter Short of NREL, the WinDS model is being modified to include the on-site use of wind-generated electricity to produce hydrogen through electrolysis. Development of the base WinDS model began at NREL in 2002 and the *WinDS-H2* modification began in June 2003. WinDS is a multi-regional, multi-time period model designed to estimate the market potential of wind energy in the U.S. for the next 25-50 years under different technology development and policy scenarios. More details on the characteristics and assumptions in the model are included in the presentation, located at http://www.eere.energy.gov/hydrogenandfuelcells/hydrogen/wkshop-wind-hydro.htlm

The second analysis project, presented by LeeJay Fingersh of NREL, is a modeling effort to evaluate the best technical approaches to combine hydrogen production with wind power systems. The *WindSTORM* model will conduct wind-hydrogen interface optimizations incorporating electrolyzer, fuel cell, and battery systems. It will simulate the calendar year 2002 using California ISO load data and wind farm data from Lake Benson. MN. The model will examine different configurations and control methods compared to a "base case" system that includes a rectifier, electrolyzer, compressor, variable speed drive, hydrogen storage container, wind turbine, fuel cell, and inverter. Hybrid system designs are being examined that include hydrogen storage in the wind turbine tower, nickel hydrogen batteries to store electricity, and combined controller and power electronics

Figure 1: Role of Wind and Hydropower in Hydrogen Production

"Strawman" Vision

In the near term (present-2015), wind power will contribute to hydrogen production primarily in smaller-scale, distributed applications, consisting of wind turbines providing power to electrolyzers, often in conjunction with other power, storage, and control components in hybrid system architectures. Hydropower based hydrogen production will be used for grid based electrolysis in regions where hydropower or other low-carbon electricity sources dominate and at previously undeveloped hydro sites by adding small scale power generation to existing reservoirs or using flowstream kinetic turbines to power electrolyzers. Demonstration projects underway include city-scale, municipal systems receiving renewably produced hydrogen, and wind/hydro electrolysis production delivered via existing hydrogen pipelines or in natural gas pipelines as hythane. Applications will include hydrogen supply for local transportation fleets and emerging stationary distributed power applications. Production costs will be substantially higher than competing hydrogen sources, but overcome by technology development support, green energy drivers, and/or lack of supply alternatives. For some scenarios, co-production of electricity and hydrogen offers opportunities for optimum facility economics, and improved utilization of electricity transmission lines. Studies indicating viability of larger-scale, including offshore, wind and hydropower-based production, backed by validated successes of distributed-scale applications, will influence production scenarios in hydrogen and electricity infrastructure planning.

In the mid term (2015-2030), distributed applications will begin steady growth to meet growing hydrogen transportation and stationary power demand. Several co-located wind and hydro-based hydrogen electrolysis facilities will be in operation, providing bulk hydrogen delivered by truck, rail, or ship, and later pipeline delivery. Facilities have capability of marketing both hydrogen and electricity, in whatever combination needed to optimize against production needs, economic drivers, and other constraints. Wind power facilities may take advantage of turbine towers for hydrogen storage compressed at low pressures (150psi) by electrolyzers to be utilized for local demand or as a reserve to pipeline demand. Hydropower production will be based on use of off-peak available capacity. Production costs will be somewhat higher than competing technologies, but justified by regional limitations in supplying hydrogen produced by other means, hedging against uncertainties in feedstock supplies or prices, and growing pressure for carbon-free production. Success in developing larger-scale renewable-electrolysis based production influences energy sector and policymakers to support major regional and national level energy infrastructure investments, including hydrogen pipelines and electric power transmission and distribution systems, for large electrolysis facilities near major demand centers. Offshore wind power is utilized to provide hydrogen to major coastal load centers, shipping electricity via cable or hydrogen via ship or pipeline. New systems are leveraged to address additional challenges such as providing clean water. Additional synergies are developed with other energy technologies and industries using process oxygen including biomass/coal gasification, and wastewater treatment. Hydrogen produced from wind and hydropower electrolysis facilities is used regionally to offset natural gas reforming of hydrogen for petrochemical refinery processes or ammonia production utilizing established ammonia pipelines.

In the longer term (2030 and beyond), major pipeline and electric power system projects are in operation supporting bulk hydrogen production and delivery from large-scale grid-connected electrolysis facilities near demand centers, as well as co-located production facilities relying on pipeline or other delivery modes. Distributed wind and hydro generation, either stand alone or grid connected, serves important roles for remote applications such as interstate highways and low population density rural areas. Load growth from grid-connected electrolysis facilities is met primarily by new wind generation, off-peak hydropower capacity, and other cost-effective renewable generation sources within the grid operating control area. Grid control system are in place to allow for real time electricity supply/demand monitoring that enable distributed electrolysis facilities to produce hydrogen when market conditions are favorable and central electrolysis/fuel cell facilities to provide dispatchable electricity to the grid when excess hydrogen is available. Electrolysis facilities are operated in conjunction with other system generation and controllable load assets as necessary to optimize system economics while ensuring reliability. Technology advances combined with industry maturation and production volume results in economics that compete with all bulk hydrogen production methods.

systems to optimize the overall system efficiency and reduce capital costs. The model will calculate optimal system configurations, sizes and costs. More details on the model may be found at http://www.eere.energy.gov/hydrogenand fuelcells hydrogen/wkshop-wind-hydro.htlm

Comments and suggestions from the workshop participants on the two models are presented below.

WinDS-H2 modeling effort (Walter Short)

- Include a method for handling uncertainties – show ranges
- Use a known year (e.g., 2003) as a calibration year to determine if the model will accurately calculate what has happened – perhaps work with independent system operators on this
- Make sure hydrogen cost is tied to natural gas reforming
- Use of capacity factors in WinDS-H2 is a big improvement
- Need to make sure regional wind variability is reflected in the model
- Include policy factors and impacts in modeling – could potentially use outputs from ORNL's TAFI
- Examine hythane as a specific alternative for hydrogen use, especially for stationary applications
- Address electricity transmission constraints and impacts
- BC-Hydro has done a lot of work on hydrogen production from hydro
- Consider expanding project scope to North America (versus just U.S.A.)

WindSTORM wind-hydrogen configuration and control model (LeeJay Fingersh)

- Incorporate seasonal and regional wind variability into the model
- Sentech can provide real-world data from Hawaii windfarms
- Consider using space only in one section of the tower (the base section) for hydrogen storage – this may be a more practical approach

General comments on modeling efforts

- DOE will develop a process for getting ongoing feedback on the models as they progress and results are generated
- Keep them up – these are good modeling efforts that will produce useful results!

Results of Facilitated Sessions on Grand Challenges and R&D Needs

Two facilitated discussion sessions were held to get preliminary input from participants on 1) the key barriers to electrolysis production of hydrogen from wind and hydropower and 2) the research and development (R&D) needs (or other activities) that are required to overcome these problems. The results of the discussion session are captured in Figures 2 and 3 on the following pages. Key **barriers** centered around the lack of clear, realistic system goals; the inability of existing technology to perform at levels required for cost-competitive hydrogen production; and the lack of supporting infrastructure (hydrogen storage and delivery systems and electric transmission issues). More specifically, top-rated barriers included:

- The inability for existing technology to meet a 2.0-3.5¢/kWh goal (unsubsidized) and other recommended system goals, including:
    - Electrolyzer capital cost ≤ $400/kW at 50kWh/kg and 20 bar
    - Long-term goal of 75% (LHV) electrolyzer system efficiency
- Lack of broad consensus on stretch performance goals for near-, mid-, and long-term timeframes

- Lack of hybrid designs able to optimize production of both electricity and hydrogen
- Lack of optimized power packages that include the combination of renewable generation + electrolyzer + battery + fuel cell/internal combustion engine + end use application
- Lack of a realistic target price for hydrogen that incorporates the environmental value of hydrogen
- Lack of coordination with all stakeholders on the issues and opportunities – especially electric and gas utilities, automobile companies, and fuel supply companies
- Insufficient understanding of the synergies and opportunities associated with co-locating wind and pumped hydro storage
- Hydrogen cannot be stored cheaply and efficiently

A number of **R&D needs** were identified, with the top-rated needs grouped into five categories, as shown in Figure 3: 1) deployment to early markets; 2) modeling and analysis; 3) technology development; 4) hybrid systems engineering; and 5) interaction and collaboration. The highest-priority needs included:

- Conduct an analysis of the environmental and economic benefits of using domestic, renewable energy sources for hydrogen production (that calculates the true cost of energy alternatives by providing cost values for externalities including environmental, social, energy security and reliability factors)
- Fund development of larger-scale electrolyzers with larger surface areas to explore economy-of-scale benefits and potential for bulk production (in collaborative partnerships among technology developers, utilities, and government).
- Conduct large-scale wind/hydrogen demonstration project (100+MW) that sells hydrogen to an existing market (e.g., hythane or industrial hydrogen pipelines)
- Develop low-cost, efficient power electronics for electrolyzers that would be optimized for use in wind/hydro applications (high efficiency, low cost, AC-DC and DC-DC, grid connected and direct connected)
- Develop system requirements for integrated wind turbine-electrolysis systems
- Establish ongoing industry stakeholder group to continue discussions
- Using DOE's study of undeveloped (existing dam) hydro sites as a starting point, conduct a study that overlays potential wind sites to determine scope of potential for co-located wind/hydro

Next Steps

The *Workshop on Electrolysis Production of Hydrogen from Wind and Hydropower* was a key step in developing a more comprehensive strategy for pursuing the potential of these renewable energy resources for domestic hydrogen production. Next steps were identified around each of the workshop's three goals, as summarized below.

1) A productive dialogue was initiated among representatives from the wind, hydropower, and electrolysis industries, and participants strongly supported the idea to continue and expand the dialogue among a larger group. DOE will pursue the recommendation to form an industry working group to further synthesize the results of this workshop and to develop recommendations for future activities. The working group will be expanded to include additional stakeholders, especially representatives from utility companies, automobile companies, energy companies, international companies and organizations.

2) Comments received on the ongoing NREL modeling efforts and preliminary results (WinDS-H2 and WindSTORM) will be incorporated, and additional comments can be directed to Maggie Mann of NREL at margaret-mann@nrel.gov. The modeling assumptions and results will be integrated with activities of the DOE Hydrogen Analysis (H2A) team, which is working to synthesize, coordinate and expand DOE hydrogen analysis activities. The initial results from the models are expected by mid-2004 and will be made available to participants in this workshop and other interested parties for review and comment.
3) Input from workshop participants on key challenges and priority R&D needs will be used to help shape ongoing DOE RD&D directed at lowering the cost and improving the efficiency of electrolyzer, wind, and hydropower technologies. DOE will consider hosting a second workshop in 2004 to provide more detail on the specific opportunities, challenges and R&D needs associated with electrolysis production of hydrogen from wind and hydropower.

Figure 2. Grand Challenges (Page 1 of 2)

WHAT ARE THE BARRIERS (TECHNICAL & NON-TECHNICAL) TO ELECTROLYSIS PRODUCTION OF HYDROGEN FROM WIND & HYDROPOWER?

TOP PRIORITIES (▲= Industry Vote ● = National Laboratory Vote)

MARKETS/ MARKET CONDITIONING	POLICY AND INCENTIVES	TRANSMISSION, TRANSPORT AND STORAGE	ELECTROLYZERS AND ANCILLARY EQUIPMENT	SYNERGIES/ANALYSIS
▪ Short term focus should be more on distributed stationary applications ▲▲ ▪ Lack of a future market for hydrogen delivery – need assured price for delivery of "x" kg hydrogen at a specific location ▲▲ ▪ Need to avoid "NIMBY" early – need proactive public outreach and education ▲● ▪ Market = Perceived value → ask the consumer what they want ▲ ▪ Need for more innovative uses for hydrogen in existing markets (i.e., Hythane®) ▲ ▪ Bulk hydrogen cost from steam methane reforming is $1.00 delivered -- this is unachievable through electrolysis! ● ▪ Lack of market design for "hydrogen electric economy" ▪ Need to support wind through transition to market scale ▪ Need for better understanding of regions that can produce renewable hydrogen at a cost that is competitive with fossil-based hydrogen	▪ Lack of policy to encourage a transition market ▲▲▲▲ ▪ Uncertainty over whether and for how long current government support levels for wind (PTC) will continue (need for at least another 10 years) ▲▲▲ ▪ Lack of connection between production incentives and investment incentives ▲●● ▪ Need early solicitation from DOE for large scale (100+ MW) wind/hydrogen installation ▲▲ ▪ Need for combination of technology improvements and policy incentives ● ▪ Lack of policy to mitigate investment risk ▪ Economic credit ($) for renewable hydrogen (zero emissions) needs to be quantified ▪ Externalities of fossil fuels should be internalized ▪ Need for DOE funded projects that demonstrate scaling up of electrolysis	▪ Need to better understand the synergies and benefits of co-locating wind and pumped hydro storage ▲▲▲▲▲▲●● ▪ Hydrogen cannot be stored cheaply and efficiently ▲▲▲▲▲▲●● ▪ Need to identify obstacles to adding hydrogen to existing gas pipelines ▲▲▲▲ ▪ Lack of line pipe for building gaseous hydrogen transmission pipelines that are proven capable for "Renewables Hydrogen Service" at installed cost comparable to natural gas pipelines ▲▲▲ ▪ Do not understand potential for geologic (underground) storage of hydrogen at large scale, low cost: extent, geographic location, capacity (large scale, i.e., more than 1,000 TWh) ▲▲ ▪ Lack of demonstrations of large scale hydrogen storage in - Pipelines - Underground stores ●▲ ▪ Need for transmission network optimization to support a hydrogen-electric economy ●	▪ Lack of ability to meet 2-3¢/kwh goal with current technology: electrolyzer capital cost needs to be <$400/kw at 50 kwh/kg at 20 bar ▲▲▲▲▲▲▲▲●●● ▪ Electrolyzers must meet these goals: - Cost ≤ $400/kw - Efficiency ≥ 75% (LHV) ▲▲▲▲●● ▪ Lack of electrolyzer designs for large scale hydrogen production at pressure (2,000 psi or more) ▪ Need to improve rectifier efficiency to greater than 95% thru 10:1 turndown ▲▲▲ ▪ Economies of scale are required to prove cost reduction in electrolysis equipment – but no large-scale systems are built ▲▲▲ - Benefits of economies of scale (cost reduction factors) are not well understood ▪ Consider costs in terms of $/Kg/h electrolyzer capital cost	▪ Need to work more with electric and gas utilities as partners in hydrogen R&D and demo programs ▲▲▲▲▲▲▲● ▪ Lack of a realistic target price for hydrogen – one that includes costs of avoidance – CO_2, health, national/economic security and fuel efficiency comparisons ▲▲▲▲▲▲▲ ▪ Need for more coordination among ALL stakeholders (auto, electric power, fuels, etc.) ▲▲▲▲▲●● ▪ Lack of wind and hydropower forecasts based on a de-regulated utility industry that use price, not minimum cost, methodology ▲ ▪ Need to match renewable energy source with water supply (locations) ▲ ▪ Lack of a "renewable portfolio perspective" – need to challenge assumptions and accept that "renewable systems" can have some small non-renewable mix ● ▪ Need to identify areas where there are co-located wind resources and hydrogen demands

Figure 2. Grand Challenges (Page 2 of 2)

What are the Barriers (Technical & Non-Technical) to Electrolysis Production of Hydrogen from Wind & Hydropower?

Top Priorities (▲ = Industry Vote ● = National Laboratory Vote)

Codes and Standards/ Regulations	Systems Engineering	Technical/Cost Goals	Vision	Environmental
▪ Codes and standards need to be established to enable siting, piping, delivery and use ▲▲● ▪ Need to address "human factors" impediments – (perception, codes, etc.) ▲● ▪ Lack of regulations that provide financial support for large-scale demos ▪ Need to change spinning reserve regulation to allow it to meet interruptible loads ▲ ▪ Impediments to hydropower licensing	▪ Lack of hybrid designs able to optimize production of both electricity and hydrogen ▲▲▲▲▲▲▲▲▲●● ▪ Lack of optimized power packages that include a combination of renewable generation + electrolyzer + battery + fuel cell/internal combustion engine/turbine + applications (end use) ▲▲▲▲▲●●● ▪ Lack of designs/systems for "wild" power (vs. grid connected) ●	▪ Develop the economical renewable power supply for producing hydrogen ▲▲▲▲ ▪ Wind technology breakthrough will be required to reach 2¢/kWh goal ▲▲ ▪ Hydrogen storage on vehicles is low density -- what about synthetic fuels? ● ▪ Impedance matching problem between wind generation shaft and electrolyzer cells ● ▪ 2¢/kWh unsubsidized is not realistic -- 3¢/kWh is more realistic ▪ Need to identify how 2¢/kWh or less wind power fits in to today's electric market ▪ Goals can be confused when comparing proven technology with concepts	▪ Define goals much better - Near (≤ 2015) - Mid (2015 – 2030) - Long (>2030) ▲▲▲▲▲▲▲▲ ▪ Lack of multi MW- to GW-scale electrolyzers ▲▲ ▪ We need to focus on RD&D not R&D (demonstrations are needed to prove and advance this technology) ▲▲ ▪ Need to develop a concise, credible, and compelling '"story" for the benefits of electrolysis production of hydrogen from wind and hydro ▲ ▪ Lack of definition of necessary system efficiencies and capacities ● ▪ Lack of electrolysis systems that can reliably cycle (0% - 100%) in 5 minutes ▪ Need to develop both a centralized vision and a distributed vision ▪ Vision should mention synergy with clean water production	▪ Water supply limits – assess water management issues ▲▲▲▲▲● ▪ Do not understand potential synergy and cost benefits of oxygen as an electrolysis byproduct for biomass and coal gasification ▲ ▪ Compare apples to apples – consider environmental drivers

Figure 3. Key Needs (Page 1 of 2)

What R&D (or Other Efforts) Are Needed to Overcome Barriers to Electrolysis Production of Hydrogen From Wind and Hydropower?

Top Priorities (▲= Industry Vote; ● = National Laboratory Vote)

Storage and Delivery	Deployment to Early Markets	Modeling and Analysis	Technology Development (R&D)	Hybrid Systems Engineering	Interaction and Collaboration
▪ Develop hydrogen storage systems/pipelines for stationary hydrogen applications ▲▲▲▲ ▪ Storage is a big R&D area that will require multiple research pathways and large amounts of R&D funding (larger RFPs are needed) ▲ ▪ Develop cost-effective hydrogen storage ▪ Nickel-hydrogen battery RD&D with hydrogen storage in wind tower ▪ Develop materials to overcome problems associated with Hythane® transport in natural gas pipelines	▪ Conduct a large scale wind/hydrogen demonstration project (100+ MW) selling hydrogen into existing markets (Hythane® or industrial hydrogen pipeline, etc.) ▲▲▲▲▲● ▪ Conduct demonstration in partnership with utilities: hydroelectric-hydrogen with storage ▲▲▲▲▲ ▪ Design, build, and operate a renewable hydrogen transmission demonstration facility ▲▲ ▪ Demonstrations are needed as part of a "bootstrapping" process to development of cost-competitive commercial technologies (R&D lowers costs, allowing demonstrations, resulting in first commercializations, which further lower cost, feeding back to R&D, and so forth)	▪ Conduct an evaluation of the environmental and economic benefits of using domestic and renewable energy sources for hydrogen production ▲▲▲▲▲▲▲▲ - Cost externalities including environmental, social, and energy security/reliability impacts ▪ Identify wind sites and undeveloped (existing) dam sites ▲▲▲▲▲▲●● - Piggyback onto 30,000 MW low head, low pressure hydro study ▲ ▪ Sponsor a collaborative study (GAO-DOE, NAS-DOE?) on the true costs/value of energy sources ▲▲▲▲ ▪ Focus on class(es) of assets where economics and operating metrics are most favorable (power/water/wastewater) ▲▲ ▪ Research economic stimulus "potential" – (Danish example) ▲ ▪ Conduct analysis of (several) grid-supplied, large electrolysis with large (new) green energy input – for a region ▲ ▪ Develop a comprehensive cost model joining renewable electric and hydrogen electrolysis systems ●	▪ Conduct research to develop efficient scaled-up electrolyzers ▲▲▲▲▲▲▲ ▪ Develop low cost, efficient power electronics for electrolysis ▲▲▲▲▲▲● ▪ Conduct RD&D on large scale, high pressure electrolyzer with electric utility industry ▲▲▲▲▲ ▪ Develop high performance, durable and low cost cell separators/ electrolytes ▲▲▲▲ ▪ Develop technology for high efficiency hydrogen purification ▲▲▲ ▪ Develop new wind technology with low O&M, engineering costs ▲▲ ▪ Develop multi-MW scale wind-hydrogen vehicle projects ▲ ▪ Need 2.5¢/kWh power to make case for electrolysis!	▪ Develop integrated wind turbine-electrolysis systems ▲▲▲▲▲● ▪ Fund large-scale hydro/wind demonstration project for hydrogen production ▲▲▲● ▪ Test composite reinforced line pipe (CRLP) under renewables hydrogen service conditions ▲▲▲ ▪ Identify and support hybrid systems to reduce costs ▲▲▲ ▪ Develop coupled system with wind/hydro/other electricity generation, pumped hydro storage, and electrical system ancillary service needs (like black starts) ▲▲▲	▪ Develop a hydrogen-green power educational program model ▲▲▲▲▲● ▪ Establish ongoing industry stakeholder working group on this subject ▲▲▲●● ▪ Coordinate RD&D program with other hydrogen programs, in DOE and international research forums ▲▲ ▪ Establish an electrolysis advisory panel to establish metrics and protocols ● ▪ Conduct focus group on electrolysis production of hydrogen with other major players: auto, power, oil ▪ Monitor international activity - Coordinate - Collaborate ▪ Work with states and regions on cost-shared RD&D

Figure 3. Key Needs (Page 2 of 2)

WHAT R&D (OR OTHER EFFORTS) ARE NEEDED TO OVERCOME BARRIERS TO ELECTROLYSIS PRODUCTION OF HYDROGEN FROM WIND AND HYDROPOWER?

TOP PRIORITIES (▲ = INDUSTRY VOTE; ● = NATIONAL LABORATORY VOTE)

STORAGE AND DELIVERY	DEPLOYMENT TO EARLY MARKETS	MODELING AND ANALYSIS	TECHNOLOGY DEVELOPMENT (R&D)	HYBRID SYSTEMS ENGINEERING	INTERACTION AND COLLABORATION
▪ Develop cost-effective hydrogen storage ▪ Nickel-hydrogen battery RD&D with hydrogen storage in wind tower ▪ Develop materials to overcome problems associated with Hythane7 transport in natural gas pipelines		▪ Develop wind and hydro electric forecasts based on price- (not minimum cost-) based market models ▪ Add uncertainties to any hydrogen, wind, hydroelectric forecasts and calibrate forecast to year 2002 ▪ Continue ongoing wind analysis activities at NREL and incorporate industry input ▪ Conduct analysis of water management issues – policy impediments and synergies	▪ Develop dynamic control systems for electrolysis production of hydrogen to match requirements	▪ Do RD&D to model and demonstrate <u>hybrid systems</u> (wind-hydro-hydrogen, hydrogen- electric, wind-diesel-hydrogen, etc.)▲▲ ▪ Develop DC-DC power and demonstrate conditioning and controls for MW scale wind-electrolysis system	

Appendix A – Workshop Agenda

Tuesday, September 9, 2003

8:30 am – 9:10 am	**Welcoming Remarks** ▪ Shawna McQueen, Energetics (workshop facilitator) – Introductions ▪ Steve Chalk, Program Manager, DOE Office of Hydrogen, Fuel Cells and Infrastructure Technologies – Welcome/Perspective ▪ Peter Goldman, Program Manager, DOE Office of Wind and Hydropower Technologies – Welcome/Perspective ▪ Matt Kauffman, DOE Office of Hydrogen, Fuel Cells and Infrastructure Technologies – Review of meeting objectives and purpose
9:10 am – 10:40 am	**Presentations by Participants** ▪ Bill Leighty – Director, The Leighty Foundation ▪ Matthew Fairlie –Vice President and Chief Technology Officer, Stuart Energy ▪ Ellen Liu – GE Wind Energy ▪ Dan Reicher – Executive Vice President, Northern Power Systems
10:40 am – 10:50 am	BREAK
10:50 am – 12:00 pm	**Open Discussion of Sample Wind/Hydro Hydrogen Vision**
12:00 pm – 1:00 pm	LUNCH
	Presentations on Wind-Hydrogen Modeling Efforts
1:00 pm – 1:15 pm	Mark Paster, DOE Office of Hydrogen, Fuel Cells and Infrastructure Technologies – Overview of DOE Hydrogen Program feedstock and delivery efforts
1:15 pm – 1:30 pm	Maggie Mann, National Renewable Energy Laboratory – Overview of past analyses and current modeling efforts
1:30 pm – 2:15 pm	Walter Short, National Renewable Energy Laboratory – Overview of Electrical-Wind-H2 Systems (WinDS-H2) Modeling project and Hydropower Modeling Issues
2:15 pm – 3:00 pm	LeeJay Fingersh, National Renewable Energy Laboratory – Wind/Electrolysis Hybrid Technology Concepts and Overview of Wind-H2 Configuration & Control Model (WindSTORM)
3:15 pm – 5:30 pm	**Open Discussion of Modeling Efforts and Industry Feedback on Study Plans and Assumptions**
5:30 pm	ADJOURN

Wednesday, September 10, 2003

8:30 am – 8:45 am	Shawna McQueen, Energetics (workshop facilitator) – Instructions and review of agenda
	Facilitated Sessions on Grand Challenges, R&D Needs and Priorities
8:45 am – 10:15 am	***Session 1:*** What are the grand challenges/barriers (both technical and non-technical) to achieving the vision(s) discussed during Day 1?
10:15 am –10:30 am	BREAK
10:30 am – 12:15 pm	***Session 2:*** What R&D or other activities are needed to overcome these barriers?
12:15 pm – 1:15 pm	LUNCH
1:15 pm – 2:00 pm	***Session 3:*** Review and discuss results.
2:00 pm – 2:15 pm	Conclusions and Next Steps
2:15 pm	ADJOURN

Appendix B – Final List of Participants
Workshop on Electrolysis Production of Hydrogen from Wind and Hydropower

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