


# Renewable Hydrogen Forum

## A Summary of Expert Opinion and Policy Recommendations

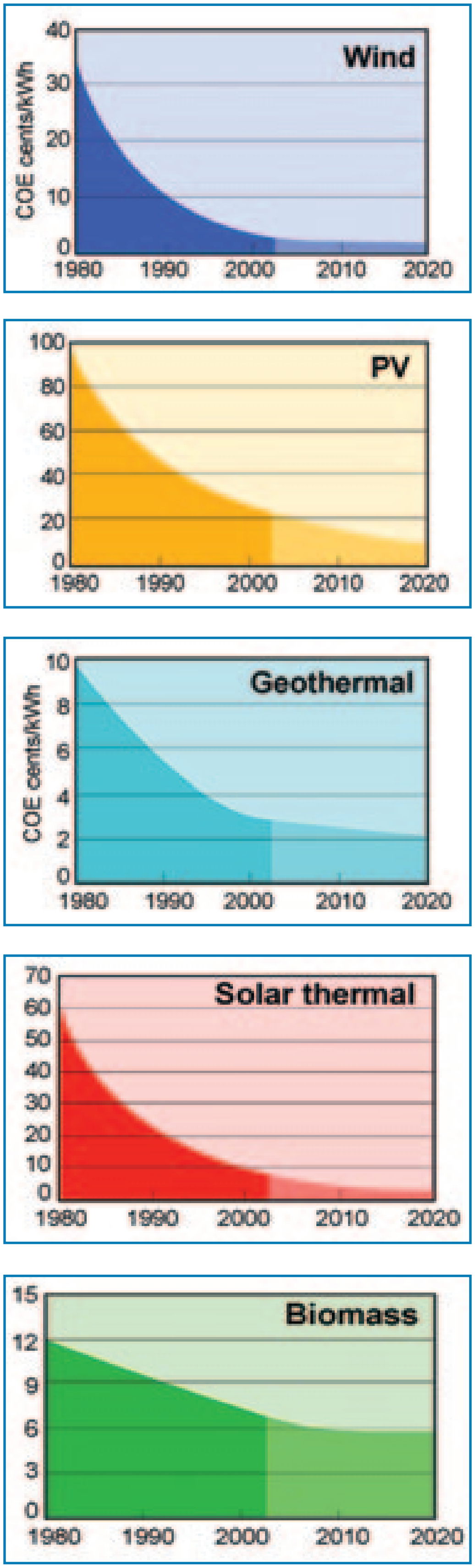
National Press Club
Washington, DC
October 1, 2003

Forum Presented By:
**American Solar Energy Society**
Hosted at World Resources Institute

Prepared by
Paulette Middleton,
Ron Larson,
Mike Nicklas
and Brad Collins

## *The Cost of Renewable Energy*

***Levelized cents/kWh in constant $2000***




***Source:*** ***NREL Energy Analysis Office***
***These graphs are reflections of historical cost trends NOT precise annual historical data.***
***Updated: October 2002***

## Photo Credits

**Cover (from the top):** NREL PIX 04745, the wood gasification unit at the McNeil Generating Station of the Burlington, Vermont Electric Department; NREL PIX 05377, Scientific Application International Corporation's heliostat system for central receivers; NREL PIX 02184, Solar Two heliostats of the Southern California Edison Plant in Dagett, California (courtesy of Joe Flores); NREL PIX 08846, Parabolic trough collection filed near Phoenix, Arizona; NREL PIX 01242, a wind turbine farm located in Palm Springs, California.

**Inside Front Cover: The Cost of Renewable Energy** charts developed by the NREL Energy Analysis Office.

**Inside Back Cover (from the top): Renewable $H_2$ Production via Electrolysis** diagram courtesy of Margaret Mann, NREL; **Hydrogen Facilities and Good to Excellent Renewable Energy Resources** map developed by the Resource Assessment Group at NREL.

**Back Cover (from the top):** NREL PIX 05559, The Leathers geothermal power plant in Imperial county, California; NREL PIX 10805, photovoltaic array located on the canopy of the BP gas station in Fairfield, California (courtesy of BP Solar); NREL PIX 01007, Fast-pyrolysis from non-food feedstocks in the process development tank at NREL; NREL PIX 03978, the Praxair, Inc., hydrogen production facility in Niagra Falls, New York (courtesy of Praxair, Inc.); NREL PIX 03034, photovoltaic used to help power fueling facilities for hydrogen-powered buses at the SunLine transit Agency in Thousand Palms, California (courtesy of Leslie Eudy); NREL PIX 04242,parabolic trough collectors used to heat water at the Jefferson County Jail, Golden, Colorado.

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In Cooperation with:
American Hydrogen Association
American Lung Association
American Wind Energy Association
Environmental and Energy Study Institute
Hydrogen Now!
National Hydrogen Association
Solar Energy Industries Association
The Wirth Chair in Environmental and Community Development Policy
World Resources Institute
Worldwatch Institute

*Hosted at World Resources Institute*

*Prepared by*
*Paulette Middleton, Ron Larson, Mike Nicklas and Brad Collins*

## Renewable Hydrogen Forum

The Renewable Hydrogen Forum brought together many of the top scientists, researchers, business leaders and economists involved in hydrogen and renewable energy to more clearly define the:

- Current and projected potential for renewable hydrogen
- Benefits to society if our hydrogen future was fueled primarily by renewable energy
- Research and development efforts needed to maximize the potential of renewable energy

The complicated nature of the issues as well as the variety of ideas presented led to a wide range of perspectives. Although, there were debates over technologies and economics of different systems, there was no disagreement that clean hydrogen must be produced from clean energy and that renewable technologies are already offering more than just promise for the long term.

This document is dedicated to honoring the perspectives of the Forum.

*ASES – September 1, 2003 -- Boulder, Colorado*


## Acknowledgment

The American Solar Energy Society wishes to thank and acknowledge its Renewable Hydrogen Forum partners:

American Hydrogen Association, American Lung Association, American Wind Energy Association, Environmental and Energy Study Institute, Hydrogen NOW!, National Hydrogen Association, Solar Energy Industries Association, the Wirth Chair in Environmental and Community Development Policy, World Resources Institute, Worldwatch Institute.

The Renewable Hydrogen Forum was made possible in part by the financial support from:

- The Holliday Family
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- Anonymous

Finally, the American Solar Energy Society wishes to acknowledge and thank the Forum participants for their voluntary participation in this event and passion for renewable hydrogen.

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# INTRODUCTION

On April 10 and 11, 2003, the American Solar Energy Society (ASES) and its partners conducted a roundtable that addressed one of the most critical energy and environmental challenges the world faces—determining the energy path to producing hydrogen. The Forum focused on the importance and promise of hydrogen produced from renewable energy---renewable hydrogen.

ASES, along with many other renewable, environmental, and health organizations, has been promoting a renewably derived hydrogen economy--a more environmentally sound, economically stable, healthier future fueled by renewable energy. Today, awareness of the need to pursue this goal is greater than ever. Continually increasing oil and gas imports are hurting the U.S. economy. The effects of global warming are becoming pervasive. Health problems associated with fossil fuel use are impacting millions throughout the country. Oil availability and nuclear plant safety are now both critical national security problems.

As the country's needs and interest in moving toward a hydrogen future increase, efforts to understand and evaluate the options must also increase. Which path or paths will result in the most sustainable, long-term solution? Today, the fossil and nuclear industries believe that they are best suited to fuel the new hydrogen economy. Many in the health, environmental, and renewable energy fields believe otherwise.

### Forum Report Organization

This report is organized as follows:

**Forum Presentations:** The presentations and panel remarks are summarized around the common themes of the session, as follows:

- Current and Near-Term Potential for Renewable Hydrogen
- Future of Renewable Hydrogen
- Future Research Needs
- Economics of Renewable Hydrogen
- Health and Environmental Consequences of Non-Renewable Hydrogen

Highlights are given for each presentation in this report. The full power point presentations and other related materials are posted on the ASES website: http://www.ases.org/

**Forum Summary:** The summary provided at the end of this report outlines many of the main points presented at the forum and provides references to most participants who discussed these topics.

# FORUM PRESENTATION HIGHLIGHTS

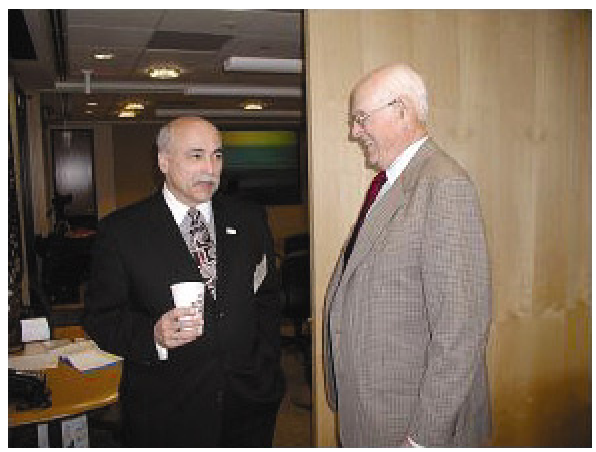
## WELCOME

The Forum was welcomed on Thursday, April 10. Mike Nicklas, American Solar Energy Society (ASES) Chair, provided an overview of the Forum history and objectives. Jonathan Lash, President, World Resources Institute, discussed the World Resources Institute mission in relationship to the Forum.  Ron Larson, Forum Chair and Member of Board of Directors, ASES, provided guidance for the Forum process and introduced the participants.

### *Mike Nicklas – Chair, ASES*

The American Solar Energy Society was created in 1954.  Through our various chapters we have about 10,000 members in the United States.  We have always focused on solar energy in a very broad sense.  We embrace the whole gamut of technologies that are directly or indirectly derived from solar energy— from wind to biofuels. A few of our technologies have actually been used in the production of hydrogen and most of the key players are in this room today.

**Although the benefits of the hydrogen economy are still years away, our biggest challenges from a sustainability standpoint are here today.** The decisions that we make, as a country, the research that we choose to support and the demonstration projects that we fund now, will no doubt determine our hydrogen future and whether ultimately we will be fueled by either environmentally sound renewable options or non-sustainable approaches.  ASES' goal has been to join with as many organizations as we can and to bring focus to these issues.  I think it's a very timely issue for us. Our collective efforts will determine our success.   Thank you all for joining in this most important step.



Anthony DeLucia, Maury Albertson

***Jonathan Lash – President, World Resources Institute***

It used to be that if you mentioned hydrogen the reaction you got was, "It's theoretically possible but it's not part of our lives." Now the question I get is, "Where are you going to get the hydrogen?" This is a huge step forward. The issues discussed at this Forum are the key issues in this debate. The role for the people at the cutting edge becomes an important one—to define the best possible transition to the hydrogen economy.


Renewable Hydrogen Forum

## CURRENT & NEAR-TERM POTENTIAL

This session focused on hydrogen generation and supply technologies that are currently available or have near-term potential. Presentations on both renewable generation and delivery were presented and then followed by a panel discussion on both aspects.

### The Supply Technologies

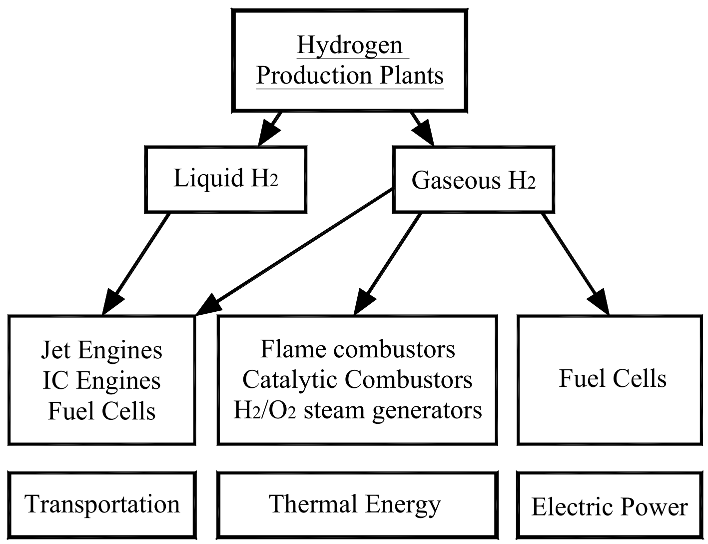
The session reviewed key near term renewable energy supply technologies in six presentations:

- Introduction to Issues & Moderator: Yogi Goswami, Vice President, International Solar Energy Society; Senior Vice President, American Society of Mechanical Engineers
- Photovoltaic/Electrolysis: Larry Kazmerski, Director, National Center for Photovoltaics, National Renewable Energy Laboratory
- Wind & PV/Electrolysis: Paul Scott, President, Stuart Energy USA
- Biomass/Pyrolysis: Danny Day, President, Eprida
- Concentrating Solar Power/Electrolysis: Gilbert Cohen, Vice President of Engineering & Operations, Solargenix Energy (formerly Duke Solar)
- Biomass: Ralph Overend, Research Fellow, National Renewable Energy Laboratory

Each of the presenters discussed various aspects of cost, resource flexibility, and availability of the technologies. The human health and environmental benefits of using renewable energy and energy security also were discussed as major drivers for renewable hydrogen.

### *Introduction to Issues – Yogi Goswami*

Hydrogen can provide a solution to the intermittency of solar energy or indirect solar energy, like wind, biomass and so on. We hear people talking about hydrogen as the clean energy source, but hydrogen is not an energy source. **Hydrogen is clean only if it's produced from clean sources. It's dirty if it's produced from dirty sources.** So, whether you use water, biomass, hydrocarbons, or coal to produce hydrogen becomes an extremely important decision. The overall hydrogen systems are summarized in Figure 1.




* Sherif, S., T. Veriziglo, and F. Barbir, 1999, "Hydrogen Energy Systems," pp. 370-402, *Wiley Encyclopedia of Electrical and Electronics Engineering,* vol. 9, J. G. Webster, (Editor), John Wiley & Sons, New York.

**Figure 1. Hydrogen Systems**

The key hydrogen energy issues that we need to consider are:

- Production
  - Feed Stock
  - Energy Resource
  - Local vs. Remote Production
  - Environmental Impact
- Storage, Transportation and Handling
  - Gaseous, Liquid, Solid Storage
  - Transportation via Pipelines, Rail, Trucks
- Safety Issues in Production Storage and Transportation
  - Safety Codes and Standards

### *Hydrogen Production*

There are a number of ways you can produce hydrogen, as outlined in Table 1.

**Table 1. Hydrogen Production Technologies**

- ✓ Steam reformation (SMR)
- ✓ Thermal cracking
- ✓ Partial oxidation (POX)
- ✓ Coal gasification (CG)
- ✓ Biomass gasification (BG)
- ✓ Electrolysis
  - ✓ Grid (Coal, Nuclear)
  - ✓ Solar Photovoltaic
  - ✓ Solar Thermal Power
  - ✓ Wind
- ✓ Photochemical
- ✓ Photo-electrochemical
- ✓ Thermochemical
  - ✓ Solar Thermal
  - ✓ Nuclear
- ✓ Biological production
- ✓ Thermal Decomposition

Between 55%-60% of the hydrogen being produced in the world today is produced by steam reformation. Hydrogen is also produced via water electrolysis using electricity from the grid. Coal and nuclear are possibilities as are solar technologies, including solar photovoltaic, and solar thermal power. Wind is also an option. Advanced technologies like photochemical, photoelectric chemical, thermal chemical, and thermal chemical—the high temperature processes where solar thermal seems like an ideal resource—are also under development.

Steam methane reformation (SMR) takes a light hydrocarbon feedstock, usually methane, then reacts it with it elevated temperature steam and catalytically converts the feedstock into hydrogen. It operates at around 700°-925° C and can achieve 65%-75% efficiency. Based on an analysis for NASA completed last year, the cost for hydrogen from SMR, without adding any environmental cost on polluting fuels, was estimated at $6 per gigajoule. Due to rising natural gas costs today, the estimated cost has increased to $10 per gigajoule. There are two problems with the SMR process: carbon dioxide ($CO_2$) production and the volatile cost of the supply of methane or natural gas—unless methane is going to come from landfills and biomass. **If hydrogen is going to come from natural gas, then that cost volatility is troubling.**

Thermal Cracking (TDM), on the other hand, produces little $CO_2$ compared to SMR. For comparison, TDM yields 0.05 moles of $CO_2$ per mole of $H_2$ produced and SMR yields 0.43 moles of $CO_2$ per mole of $H_2$. In this process, natural gas flame heats up to around 1400° C. The oven is shut off and the natural gas decomposes on the bricks to carbon black and hydrogen at about 800° C. The carbon black is a valuable by-product. However, there is still an environmental concern since $CO_2$ is still emitted and we don't know the cost of this process yet.

Partial oxidation (POX) uses liquid hydrocarbons that are heavier than naphtha and catalytically converts them to hydrogen. This process achieves about 50% efficiency and operates at temperatures around 1150°-1315° C. The process consists of synthesis gas generation, water-gas shift reaction, and gas purification. Again, $CO_2$ is an output.

Coal gasification is similar to partial oxidation. However, it can use a wide range of supply fuels like coal, biomass, and residual oils. This type of plant requires pure oxygen and the coal must be pulverized prior to gasification. It can achieve about 48% efficiency and operates at temperatures around 1100°-1300° C.

Biomass hydrogen also is a gasification/pyrolysis process that can be used to generate hydrogen from biomass. The biomass must be prepared by a high temperature and pressure process. This decomposes and partially oxidizes the biomass producing a gas mixture that can be further refined. The entire process is similar to coal gasification but requires the pretreatment step. Because the fuel is biomass, it also has the important advantage of not adding more $CO_2$ into the atmosphere.

Advanced electrolysis technologies work with alkaline water, seawater electrolysis, solid polymer electrolyte, and solid oxide electrolyzer. Seawater is an interesting possibility but it has problems with chlorine and corrosion, which could be worked out. Solar-powered electrolysis can be achieved with photovoltaic and solar thermal power. New developments in nano rectenna conversion (i.e., 3rd Generation PV) and combined power/cooling cycle also are promising. The first two technologies already are available. Costs have come down tremendously over the past two decades and some of the new developments, like nano rectenna conversion and biological photovoltaics, could reduce future costs by orders of magnitude. Any new hydrogen production technology will be compared against steam methane reformation when it comes to commercial investment. The economics of some of these alternatives are compared in Figure 2.

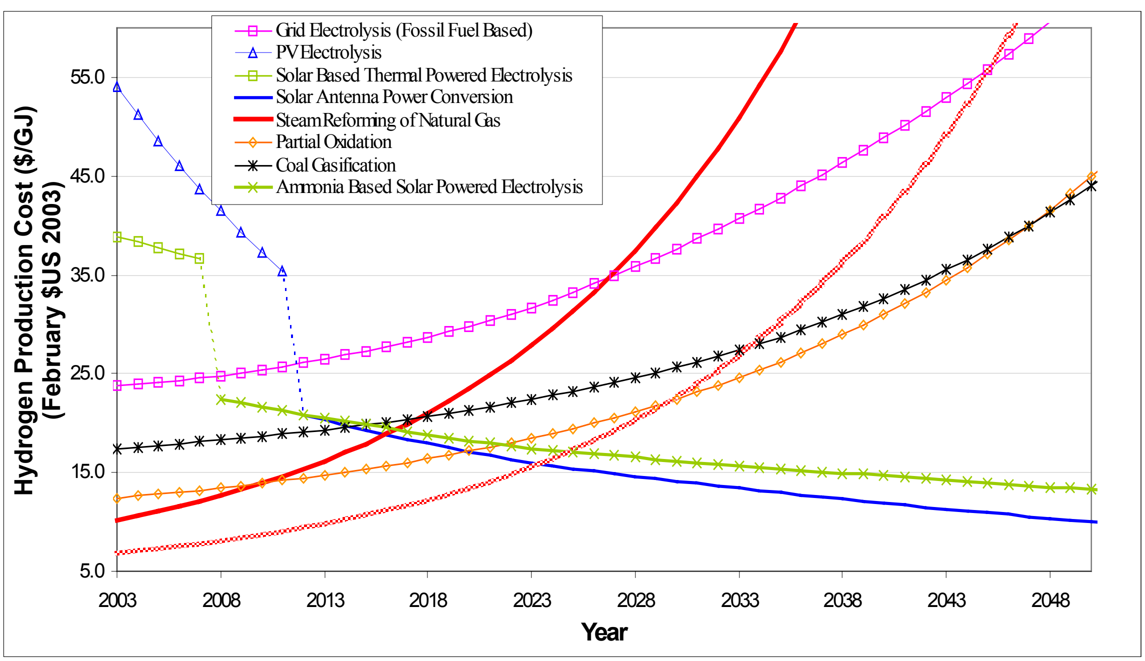



**Figure 2. Economics of Hydrogen Production Processes (February 2003 $US)**

As shown in Figure 2, **the costs based on fossil fuels are going up and the costs based on renewable energy production are going down.** In fact, the cost for steam methane reformation has gone up within less than six months. This analysis assumes that new developments in solar thermal power and photovoltaics will reduce their costs, and although not explicitly included, wind would be part of the mix right now. This analysis does not include any environmental penalty for fossil fuels, although one could argue that **there is about $15 per gigajoule ($15/GJ) in environmental costs when you use coal as a feed stock, about $13/GJ when you use petroleum as feed stock, and about $9/GJ when you use natural gas as feed stock.**

Many renewable hydrogen technologies are currently available. We need research to reduce the cost and develop additional technologies that you will hear about in this forum. **Aggressive research definitely will make the renewable option the most cost effective in the future.** If this is the case, why not invest in renewable energy processes now and accelerate the transition to renewable hydrogen?

***Storage, Transport, Handling and Safety Issues***

There are other issues that we need to address if we are to move toward a hydrogen economy. Infrastructure development is one issue. Safety codes and standards is another. We need to develop codes and standards so that people don't make mistakes. Hydrogen is a safer fuel than gasoline and others but without the right materials and the right designs, safety can become a problem.


Yogi Goswami

More details on these topics are found in the referenced documents. [1]

***PV/Electrolysis – Larry Kazmerski***

**Solar electricity is already proven in a variety of hybrid energy systems**[2,3]. Advances in photovoltaic (PV) performance over the past 25 years—with crystalline silicon more than doubling in efficiency, thin films nearly quadrupling, and concentrator cells converting almost 40% of incident photon energy into electrical power—have been the foundation for credible electricity generation[4,5]. Terrestrial PV-wind, PV-solar thermal, and PV-bioenergy continue to mark successes on the renewables side, and solar-electricity/fossil-fuel hybrids have been used in numerous applications—from grid extension, to remote power, to village power. The future of *zero-energy buildings* depends on integrated hybrid technology for energy production. Future marriages of PV with fuel cells, advanced storage, and hydrogen have become serious considerations with the growing interest in the much-touted *hydrogen economy*[6].

When the United States rolled out its hydrogen vision in 2002[7] and its strategy in 2003[8], the source of the hydrogen was perceived primarily to be natural gas. **Within a few months of the President's announcements in his 2003 State of the Union Address, the developing natural gas shortage has precluded this source from being the primary one—and other technologies have come forward. Nuclear, wind, and solar are now positioning to serve as the energy resources to produce the required hydrogen[9].** Among these resources, solar possesses some special attributes that may make it the future power of choice.

As centralized facilities, both concentrating solar power (CSP) and nuclear power provide clean-generation thermal roadmaps toward generating economical hydrogen as defined in the *Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan*[10]. Additionally, CSP, concentrating PV (CPV), and flat-plate PV can meet electricity prices that are needed for large- scale electrolysis. However, all these centralized approaches require long-distance transport. An alternative is to bring hydrogen delivery to the point of use. Just as the distributed solar-PV system makes use of the economics of "electricity generation at point of use," the distributed hydrogen system links "production" and "delivery" at the point of use—*distributed solar electricity* and *distributed solar hydrogen.*[11]

One of the commonly encountered myths about solar is that the land areas needed are extraordinary[12]. Although currently limited by a of lack of production capacity, **solar PV technology could match the existing generation capacity from an area less than 100 miles by 100 miles in the Desert Southwest (or from about 280 square miles in each of the 50 states based on available solar resource and a more distributed scenario)**[13,14]. Of course, as technology advances, the areas required to provide power and the power required for the process itself will decrease over time.

The table below presents a comparison of relevant costs, goals, and predictions over the timeframe 2003 through 2050. This analysis shows that even the Roadmap projections for PV fit well into an eventual hydrogen economy in the United States. But how can we get there sooner? If some of the "predictors" are off, then certainly the competition with other energy sources can bring about this ultimate solar scenario more quickly.

**Table 1. Basis for competitiveness of PV-hydrogen based on U.S. PV Industry Roadmap[15] and Hydrogen Multi-Year Plan[10]. *Italicized numbers projected from Roadmap using technology learning/experience curves*.**

| | 2003 | 2010 | 2020 | 2030 | 2040-50 |
|---|---|---|---|---|---|
| System Price | $6-$15/W | $3-$4/W | $1.50-$2.00/W | *~$1.00/W* | *~$0.50/W* |
| Electricity Price | $0.18-0.25/kWh | $0.11-0.16/kWh | $0.06/kWh | *~$0.04/kWh* | *~0.03/kWh* |
| U.S. Capacity | 0.2-0.4 GW/yr | 0.8-1.0 GW/yr | | | *1500-2000TWh/h U.S. electrical demand* |
| Targets | | 15% of new (added) U.S. generation capacity | | 10% of total U.S. generation capacity | *20-30% of total U.S. generation capacity* |
| Performance-highest (cell/module /system) | 10-20%/ 12-17%/ 8-12% | 20-25%/ 16-18%/ 15% | *22-28%/ 20-22%/ 16-20%* | *30-40%/ 25-30%/ 20-25%* | |
| | | | | | |
| Distributed Hydrogen: Solar Park (Electrolysis)<br>Total Price<br>Electricity Price | <br><br>$4.70/kg<br>$1.90/kg | <br><br>$2.50/kg<br>$1.60/kg | | | |
| Distributed Hydrogen: Residence (Electrolysis)<br>Total Price<br>Electricity Price | <br><br>$7.40/kg<br>$4.10/kg | <br><br>$3.80/kg<br>$2.80/kg | | | |
| Distributed Hydrogen: Photolysis (Electrochemical)<br>Price<br>Efficiency (solar to hydrogen) | <br>N/A<br>7% | <br>$22/kg<br>9% | <br>$5/kg (in 2015)<br>14% (in 2015) | | |

On the other end of the spectrum, super-high-efficiency PV using quantum dots, rods, or pods, ultra-multijunctions, impurity or intermediate layer cells, thermophotovoltaics or thermophotonic technologies all pose breakthrough possibilities.

Future hybrid electricity and energy will include PV and hydrogen. The concept of the *zero-energy building* can be envisioned to expand to the *energy-plus home* by producing more energy (electricity for the residence, hydrogen for nighttime power and the family "freedom car"). The solar-hydrogen park or village, in which the solar energy and hydrogen are shared in the community, is an extension of this concept. Additional electricity can be supplied to the grid and any excess hydrogen can be sold through the community's refueling stations. The marriage between hydrogen and solar brings secure, clean energy and makes PV a *"24-hour power"* option.

Land areas for either centralized or decentralized energy production are reasonable. The decentralized approach offers the added feature that the existing or planned built environment is suited to support and integrate these technologies. Millions of acres of wilderness or desert areas are not needed, and the costs of distributing the electricity and the hydrogen are avoided. So are the concerns for regional energy availability, because solar is sufficiently abundant to meet the needs in 49 states. Hybrids with other renewables (e.g., wind and bioenergy) extend this availability to all the United States. Land area or solar resource is therefore not a showstopper.

The, "But when?" can be estimated from the predictions of the *U.S. PV Industry Roadmap*, the Hydrogen and Solar Program's Multi-Year Plans, and considerations of the learning curves for the technology. Centralized PV-hydrogen will not likely be available until the 2040 timeframe. Decentralized approaches can be reached in 2030, depending on the escalation factors for other fuels. We can accelerate these predictions by new initiatives and new investments in the solar components—similar to what has been done recently by hydrogen. Disruptive technologies, such as second-generation thin films, organics, and nanotechnologies, can accelerate the nearer term by 5 years or more. Third-generation higher-cost approaches, including quantum technology cells, ultra-multijunctions, new materials, novel structures, and novel concentrators with performances beyond 50% efficiencies, can accelerate both distributed and centralized approaches. The further investment and careful strategy-controlled path into these next-generation breakthrough technologies will benefit the learning curve to bring not only solar-PV electricity, but also solar-PV hydrogen significantly closer. These systems can become realities within a generation.

### *Wind and PV/Electrolysis – Paul Scott*

**If we grow our energy at home, we save $100 billion per year sent overseas.** Add to that the monies now being spent to "secure" the Mideast, the hundred billion or so that is traceable as an air pollution attributed health cost, additional costs for environmental damage due to air pollution, and some valuation of the possible cost to the U.S. economy of a sudden interruption of fuel supply. Together, these make a strong argument for renewables.

In addition, renewable energy sources are becoming cost effective. This is resulting in worldwide growth of the wind electricity generation capacity at near 40% per year. As suggested by the figure, continued strong growth will result in renewables becoming a major participant in electrical power generation in the coming decade. (See Figure 3).

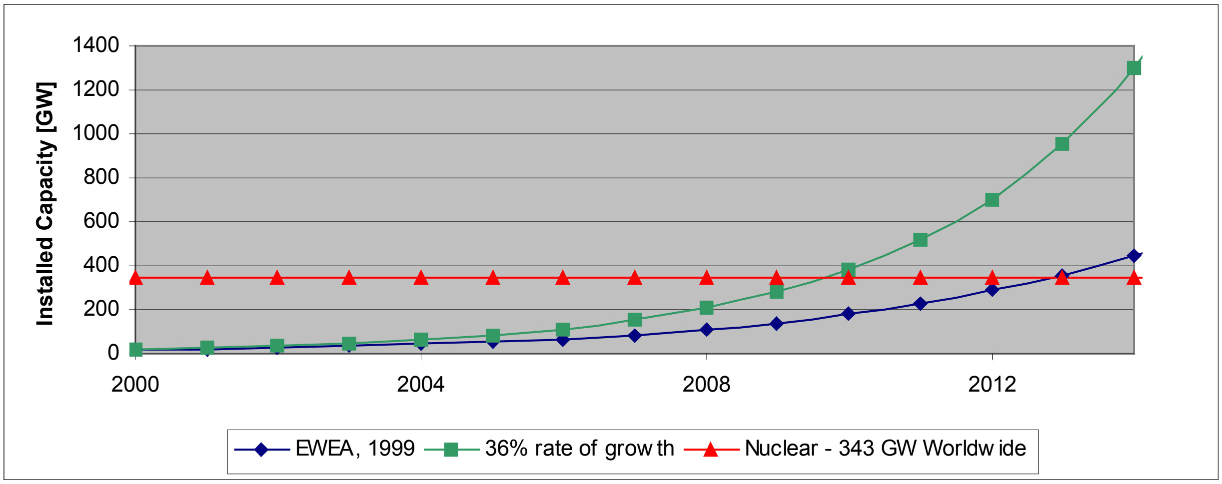



**Figure 3. Projected Worldwide Wind Generation Capacity**

The promise of wind and PV/electrolysis results from its versatility in providing both fuel and power. Wind generation can power a town when the wind is blowing and solar energy can provide power when the sun is shining. The excess power generated at these times can be used to produce hydrogen via electrolysis. When the wind is not blowing and the sun is not shining, stored hydrogen can be used to run an electrical generator and provide power to the town. Meanwhile vehicles can run on wind- or PV-generated hydrogen.

Utility Scale Wind/Hydrogen System: Palm Springs/Windtec (March 31, 2003)

In discussions of hydrogen production via electrolysis, the question about how much water is needed comes up repeatedly. As an example, the amount of water needed to power all the cars in California on hydrogen is less than 1% of the water used in the State of California. Conservation and/or desalinization could help make this amount available.

Cost is another issue. The cost of wind-generated hydrogen needed to fuel cars in the Coachella Valley is estimated to be less than ten cents a mile for the 80 kilometers-per-kilogram fuel cell car. Much of this is storage cost, due to the great variability of the wind from one part of the year to another. **In the Great Plains states the fuel cost would drop to about five cents per mile.**

Does this make sense nationwide? Renewables are widely available, although different regions may have differing means of making fuel. **If one were to take just about one-third of the billions we send overseas every year for oil and invest it in the next 20 years - we would reach these goals of energy independence.**

## *Biomass/Pyrolysis – Danny Day*

We may not be exactly sure what's going to happen to our earth, but from the standpoint of carbon as it relates to the world—we know we really don't have a choice—we have to reduce carbon. If we continue as we are, something is going to happen. For example, the evidence is building that any massive influence or tremendous difference in the change in salinity in our ocean could significantly affect and even perhaps shut down the Gulf Stream ocean currents.[16]

Gilbert Cohen, David Friedman, Martin Shimko, Yogi Goswami, Danny Day

Producing hydrogen from **biomass gives us an opportunity to sequester carbon**[17] while simultaneously producing energy. There is also the opportunity to produce materials, metals, steam, aluminum, glass, and all of our building materials; every pound will represent $CO_2$ that has come out of our atmosphere and been converted into a useful material.

Nature has been doing this for a very long time through photosynthesis. For billions of years, nature has taken material, burned it and produced charcoal. That charcoal is in our soil. Radio carbon dating tells us that charcoal is a very stable sequestered material.[18] A lot of charcoal can be added to the ground without hurting anything. As a matter of fact, it's good for the soil and it has a saleable value as a nutrient carrier and soil amendment. Adding charcoal to soil increases crop growth increases by 5%-6%[19] Others have reported even higher numbers [20,21]

For roughly every million Btus of hydrogen produced from biomass, somewhere between a minimum of 91 kilograms, and probably closer to 150 kilograms of carbon dioxide[22], will be sequestered, depending on the type of biomass used and fertilizer made.

## *Concentrating Solar Power (CSP)/Electrolysis – Gilbert Cohen*

Concentrating solar power is a first-class renewable power. It is a proven technology, has abundant resources, firm capacity, reliability and dispatchability, cost reduction potential with mass volume production, and it is environmentally friendly. The main CSP technologies are power towers, parabolic dishes, parabolic troughs, concentrating PV, and roof integrated systems. With a proven commercial success and more than ten years of operational history of 354 MWe, CSP technologies are well positioned for increasing level of market penetration in the coming years.

In terms of making hydrogen, the parabolic trough can already be used for direct production of electricity for the electrolysis process. These plants are very economical. **They have a life expectancy of at least 30 years and with conventional financing can be fully paid in 20 years. After that, the fuel is free and the Operating and Maintenance (O&M) cost amounts to only about 2.5 cents/kWh in today's dollars. In 2023, the costs would be more like 6-7 cents/kWh.**

### *Biomass – Ralph Overend*

**Biomass is already the world's fourth foremost fuel.** The future potential of biomass is a function of land and energy competitions. Urbanization and the need for fiber, management of water, and food conservation compete with use of land for energy crops. Both the U.S. and the world have significant biomass capability. (See Figure 4). Biomass complements wind and solar resources, since there is little overlap in regions where a resource is highest.

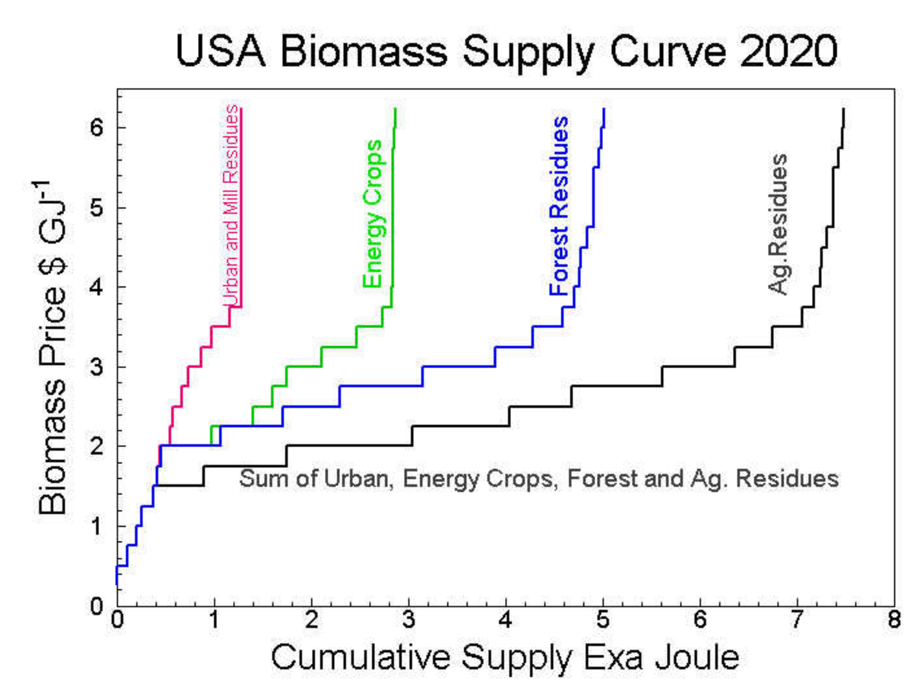



**Figure 4. Projected U.S. Biomass Supply Curve for 2020**

The pulp and paper industry has a long history of producing energy from biomass. The biomass that is harvested to produce pulp and paper simultaneously produces black liquor. This black liquor is an energy form as well as a chemical recovery system in the pulp and paper industry. Today, post-consumer biomass materials, in the form of municipal solid waste, landfill gas, and industry waste, represent a very rich resource, which is already fully concentrated and doesn't need to be harvested.

In the last 30 years or so, the biomass contribution to the U.S. economy has doubled. Today, we have a very diverse biomass-based energy economy. We can look out over the next 20 years and look at the resources—the total amount of biomass—that will be available for less than $3 per million BTU or $3 per gigajoule. In the case of forest residues and agricultural residues, increasing the price paid will increase the supply significantly. In the case of energy crops, competition with existing food or fiber production must be taken into account.

Current biomass-to-hydrogen technology is based on gasification or pyrolysis. Gasification is a very flexible technology that is being developed in various biomass and bioenergy programs around the world. In terms of economics, the costs to produce hydrogen via biomass pyrolysis can be brought down into the range of $1.50 per gasoline gallon equivalent.

By about 2020, the hydrogen potentials are estimated be about 29 teragrams of hydrogen from about seven exajoules of biomass. This is equivalent to about 40% of today's vehicle fleet and would require only about 17 million hectares of energy crops. In terms of greenhouse gas savings, this translates to about 84 million metric tons of carbon equivalent fuel. Post-2020 improved process efficiency of about 10% is projected. High-yielding energy crops would reduce the cost of biomass and the amount necessary by about 25%. By developing appropriate crops, we would be able to access more marginal land with adapted crops.

For more details, please see this reference.[23]

## The Delivery System

This session reviewed the delivery systems and included the following five presentations:

- Introduction to Issues & Moderator: Jeffery Serfass, President, National Hydrogen Association
- Vehicles: David J. Friedman, Senior Engineer, Clean Vehicles Program, Union of Concerned Scientists
- Centralized Wind: Bill Leighty, Director, Leighty Foundation
- Decentralized Technologies: Martin Shimko, Vice President for Business Development, Aválence
- Decentralized Technologies: Jonathan W. Hurwitch, Sr. Vice President, Sentech, Inc.

### *Introduction to Issues – Jeffery Serfass*

The main issues that need to be considered for delivery of renewable hydrogen are delivery of hydrogen from bulk production, delivery of renewable resources to local hydrogen production, and delivery of useful energy. We need to consider whether solar is economical for local hydrogen production avoiding all delivery issues. Perhaps the quintessential question to ask is, **"Is it more economical to move hydrogen or electricity?"** What about the possibilities for storing hydrogen in pipelines?

### *Vehicles – David Friedman*

**Cars and trucks are responsible for about 70% of the energy use in the transportation sector.** Although buses are responsible for less than 1% of the energy use, bus fleets are a great place, potentially, to begin using hydrogen in vehicles.

The potential for fuel cell vehicles is great and could help the U.S. achieve 100% renewable hydrogen by 2030. Under this fuel-cell vehicle scenario, the hydrogen requirement is basically one quad in 2025, which is only a fraction of the amount of electricity we would be producing at that time. **So renewable hydrogen for the transportation sector, in this 2025 timeframe, would not really stress the electricity infrastructure.** Note, however, that because of fleet turnover, greenhouse gas emissions still won't be eliminated in this scenario.

David Friedman, Sivan Kartha, Danny Day, Elaine Wilson, Tony DeLucia

Hydrogen is not necessarily clean by definition. The general public needs to understand that *only* when the vehicles are fueled with hydrogen derived from renewable energy is hydrogen clean. **Fossil fuels are a very dirty source of hydrogen. For transportation, local reforming of natural gas, the least dirty of the fossil fuels, is probably the most likely option, whereas renewables are the longer-term option.**

### *Centralized Wind – Bill Leighty*

**The Great Plains wind resource is enormous. It is about 10,000 terawatt hours a year from just the twelve windiest states.[24] That is about equal to the entire energy production, from all sources, in the US. So, wind could literally run the country.** However, it is 'stranded" – there is no transmission for it and no may to get it to market.

How will distant markets access the very large, stranded, renewable energy resources of the Great Plains – primarily wind and biomass? Are new, large-scale hydrogen transmission pipelines an alternative to new electric lines? Is it more acceptable to put pipelines under people's backyards than electric lines over them?

Figure 5 shows a full system diagram of the connections.

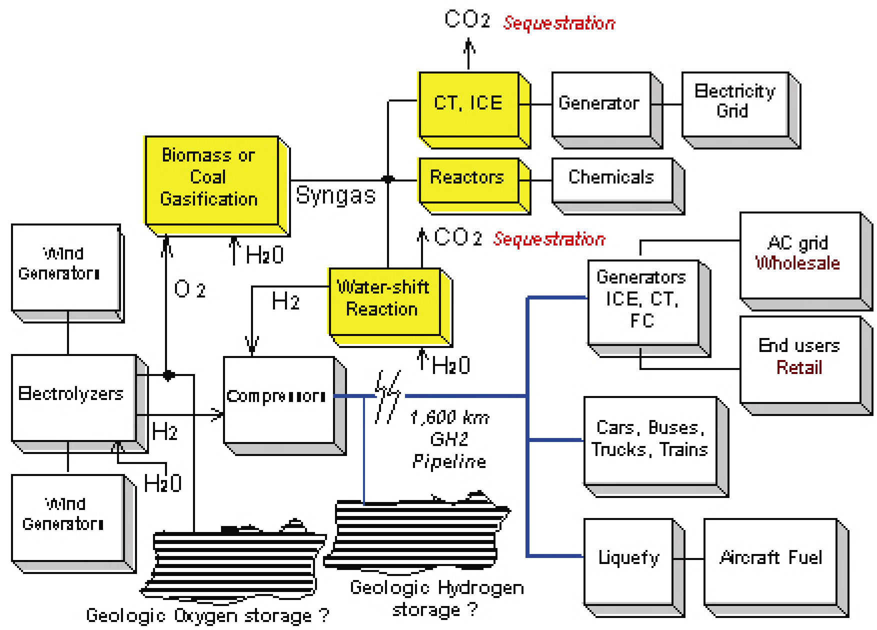



**Figure 5. Full System Diagram of the Connections**

Extant electric lines could carry only an insignificant fraction of the potential renewable production. About 400 new 36-in gaseous hydrogen ($GH_2$) pipelines or about 900 of the largest possible new electric lines would be needed to get all of the potential production to market.[25] The capital cost for the two alternatives is comparable.

The costs of delivering hydrogen fuel from the huge North Dakota wind resource to Chicago were estimated as part of "Repowering The Midwest", the clean energy plan for the electricity industry, by ELPC, Chicago, and are summarized in Table 3.[26,27] Assuming the installed capital cost of large, new wind plants is only $700/kW, and if electricity is delivered in Chicago at wholesale, the only profitable case is an electric transmission scenario. **But if we're delivering hydrogen fuel in Chicago, it's different. Now we're competing with hydrogen produced from natural gas by SMR.**

**Table 3. Retail Price of Wind-Generated Hydrogen Fuel Delivered to Chicago (with Subsidy)**

| | |
|---|---|
| Wind-generated electricity in ND | \$0.045/ kWh |
| Federal PTC (production tax credit subsidy) | (0.017) |
| Subsidized wind energy in ND | 0.028 |
| Hydrogen conversion and 1,000-mile transmission | 0.052 |
| Wholesale price of gaseous hydrogen ($GH_2$) fuel in Chicago, end-of-pipe | \$0.08/kWh |
| Equivalent per-gallon-gasoline-energy price* | \$2.89/gal |
| Distribution and fuel station cost | \$0.79 -1.45/gal |
| Retail price of $GH_2$ fuel in Chicago | \$3.68 - 4.34/gal |
| Drive train efficiency ratio: FCEV/ICEV=2 | |
| Equivalent retail price $GH_2$ fuel per vehicle mile | \$1.84 - 2.17/gal |

* 1 GJ=278 kWh; 1 gallon gasoline=0.13 GJ(higher heating value)=36 kWh@\$0.08/kWh=\$2.89/gallon

Time-varying renewable energy sources can be converted to hydrogen gas for long-distance transmission in high-capacity pipelines as compressed $GH_2$, with the important advantage of energy storage. For example, a 1,000-mile long, 36-in diameter pipeline, operating at 1,000 psi, will store 120 GWh (120,000 MWh) of energy if the customers at the destination draw down the pressure to 500 psi. The same pipeline "packed" to 2,000 psi, then "unpacked" to 1,000 psi, for instance if the wind stops blowing for two or three days, would store about twice as much energy, about 240 GWh. Additional large-scale $GH_2$ energy storage may be economically available in geologic formations underground. We know that solution-mined salt caverns are adequately tight; other geologic formations might be as well. This needs to be studied, especially for the Great Plains. **Geologic storage could greatly multiply the storage capacity available in the pipeline(s), perhaps to seasonal-scale, making renewables "firm" and "dispatchable" energy resources, greatly enhancing their value. Since electric transmission provides no storage, this costly investment would operate at about the same capacity factor (CF) as the generation source-- about 40% for Great Plains wind. This is a heavy cost burden for renewable-source energy delivered to markets as electricity.**

Gilbert Cohen, David Friedman, Martin Shimko, Yogi Goswami, Danny Day, Ralph Overend, Larry Kazmerski

Pipeline transmission of $GH_2$ will probably cost 50%-75% more, per unit energy, than pipeline natural gas[28], because:

- $GH_2$ has only one-third the energy density, by volume, of natural gas
- Special materials must be used in pipelines and fittings to avoid hydrogen-induced cracking
- Special valves, meters, joints, and fittings must be used to prevent excessive leakage of $GH_2$

The oxygen byproduct of electrolysis is valuable to adjacent biomass and new "near zero emissions" coal gasification plants, also enhancing the value of hydrogen production from renewable sources like wind.

### *Decentralized Technologies – Martin Shimko*

Decentralized technologies focus on using onsite renewable resources to produce hydrogen onsite, for use onsite. To do this, different combinations of fuel cells, hydrogen fueled internal combustion (HICE) vehicles, renewable energy, electrolyzers, and storage that make sense economically for a given set of circumstances are under evaluation. For example, a brown-field is being reclaimed for use as a commercial, industrial, residential development site and planning to utilize onsite hydroelectric power availability to address multiple needs of: parking lot lighting (direct electricity use), maintenance vehicle fueling (electrolysis, storage, HICE fueling), and peak shaving (electrolysis, storage, fuel cell). The amortization period of 10 years dictated by present capital costs is consistent with the overall project financing. This type of approach is not economically attractive everywhere at this time but, as prices come down, more and more economically advantageous scenarios will be identified. **To make this happen, government/industry partnerships to reduce fuel cell costs and stronger government incentives that promote renewable power and incorporate environmental impact considerations are needed.**

### *Decentralized Technologies – Jonathan Hurwitch*

Hawaii has unique energy needs. Except for renewables, Hawaii imports all of its energy; there are no indigenous fossil fuels. Hydrogen can be produced from Hawaii's indigenous resources and can be the medium for both electricity and transportation fuels.

Jonathon Hurwitch, Jeff Serfass, Bill Leighty, Peter Devlin

Like every state, Hawaii would like to develop a high tech industry around hydrogen. Three years ago, Hawaii's legislature mandated that their State Energy Office conduct a hydrogen feasibility study. The study found that, assuming that fuel cell cars and trucks are available and competitive with internal combustion engines within the next 10-20 years, hydrogen makes sense as a transportation fuel for Hawaii. Fuel cell cars will beat gasoline powered cars in Hawaii, even with very modest or no escalation in gasoline prices, because the gasoline price equivalent of hydrogen produced within the state is much lower than price of gasoline imported to the state. **The recommendation was that Hawaii ought start developing hydrogen because it is likely to be economical there sooner than in other places.**

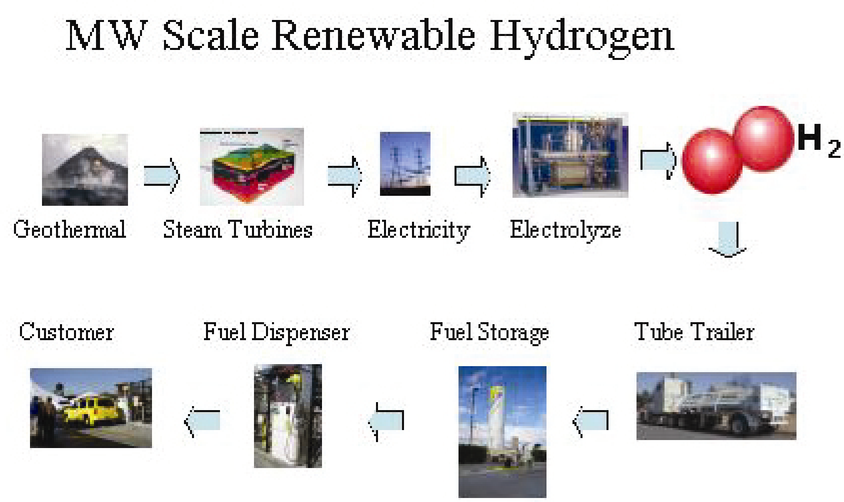



**Figure 6. MW-Scale Renewable Hydrogen**

## Panel Discussion

The participating panel members were:

- Peter Devlin, Hydrogen Production and Delivery Research Leader, US Department of Energy
- Martin Shimko, Vice President for Business Development, Aválence
- David J. Friedman, Senior Engineer, Clean Vehicles Program, Union of Concerned Scientists
- Jonathan W. Hurwitch, Sr. Vice President, Sentech, Inc.
- Danny Day, President, Eprida
- Paul Scott, President, Stuart Energy USA
- Jeffery Serfass, President, National Hydrogen Association

**Peter Devlin:** From a business, government or public policy standpoint, **what are the critical success factors for renewable hydrogen?** What kinds of things need to be in place for a technology to really be launched and actually go all the way and compete with some of those dirtier things that we have to deal with in terms of energy sources today?

**Bill Leighty: We need Congress to ask GAO to do a study to tell us what gasoline really costs so we can begin to internalize the external costs that are not included in the prices that we pay.**

**Peter Devlin:** Is maintaining a security system that allows us to bring in imported oil part of those costs?

**Bill Leighty:** Right, and only the GAO can give us the right answer.


Martin Shimko, Yogi Goswami, Danny Day, Ralph Overend

**Jonathan Hurwitch:** Most people don't understand where energy comes from. They understand the gasoline pump and the electricity socket in the wall but not how the energy gets there. **We need a national debate that asks the country what they want in their energy policy, because we are going have to pay for cleaner energy if that's what we want.** The reason to do hydrogen is because it's cleaner but it's only cleaner if it comes from renewable sources.

**David Friedman:** Obviously a lot of work is needed to get the cost down. **Part of what we need is vision.** Part of that vision does come from government and part of it comes from industry. If you look at the amount of money that was spent to get man on moon, we're talking about at least 1 or more orders of magnitude, more money than we're talking about right now for hydrogen.

**Danny Day:** I think the transition is going to happen a lot quicker than the petroleum industry had because of the technology we have.

**Peter Devlin:** Another good point is that **the education system fosters the kind of people that can actually make it happen.** For example, 35 years ago most people smoked and now it's hard to find anybody that does. I think that's largely due to education.

**Anthony DeLucia:** I'd like the panel's impression of the overall idea of sustainable development. It would involve our entire redesign of communities so that they are built more energy efficient and organized to be less transportation dependant.

**Danny Day:** The question is how we can measure quality of life. Because once we can measure quality of life, then it can be evaluated.

**David Freeman:** Communities have been rated based on the quality of life using factors like lack of crime, health services, the quality of schools, amount of green space and the like.

**Anthony DeLucia:** **You can also look at how costs would be lower by eliminating chronic diseases such as asthma related to air pollution and eliminate $12 billion year.**

**David Freeman:** This evolution is not going to take place by government or by laws. It will take place only if there's sufficient education of the American people. **We need to be less dependent on imported oil. That is not a debatable issue in this country.** We can do something about it. We can move this hydrogen economy forward.

David Freeman

**Harry Braun:** In the 1930's there were thousands of trucks and buses and cars with their existing engines that were modified to use hydrogen fuel and they could flip from hydrogen to gasoline with a flip of a switch while the car was on the fly. These were both in England and in Germany. **Any car on the road today can be modified to use hydrogen fuel and if you use liquid hydrogen, you'll have to same performance if not better and you'll have the same range and you won't have any of the problems that we now have with importing oil.**

## FUTURE

The second day of the forum began with sessions on the future of renewable hydrogen, future research needs and a panel discussion on the future. The following highlights help underscore the main points of Day 1 and illustrate the main challenges and necessary directions for achieving a renewable hydrogen future.

### Future of Renewable Hydrogen

This session provided a review of the Day 1 highlights and in-depth discussions of future technologies.

- Introduction to Issues & Moderator: Susan Hock, Center Director, Electric and Hydrogen Technologies and Systems, National Renewable Energy Laboratory
- Chemical: Aldo Steinfeld, Professor of Mechanical & Process Engineering, ETH – Swiss Federal Institute of Technology
- CSP/Electrolysis and Thermal: Dale Rogers, Program Manager, Boeing Energy Systems
- Algae: Ralph Overend, Research Fellow, National Renewable Energy Laboratory

### *Introduction to Issues & Moderator – Susan Hock*

Most of the hydrogen in the world currently is produced with natural gas reforming. Today, 95% of hydrogen production in the United States and about 50% in the world is produced using this process. Right now, this is the least expensive way of producing hydrogen. It's also more amenable to very large-scale production plants. Hydrogen production as part of an integrated petroleum refinery is the next most common method in use, accounting for about 30% of world production. Coal gasification accounts for about 18% of worldwide hydrogen production. Next is **electrolysis, which right now is only 4% of the production worldwide.** This method depends on having low cost electricity to make electrolysis as cost effective as possible.

Hydrogen can also be produced from biomass, using thermal processes like gasification and pyrolysis. Biomass-to-hydrogen processes also produce byproducts, which can improve the economics of these systems. Looking toward the future, there are also advanced biological processes, and uses of intermittent renewables like photovoltaics, wind, and concentrating solar power for electrolysis. There are also high temperature systems using solar thermal, geothermal, biomass, and nuclear energy. Finally there is direct water splitting, which is sometimes referred to as the Holy Grail for producing hydrogen. It's simple but it's a very long way off.

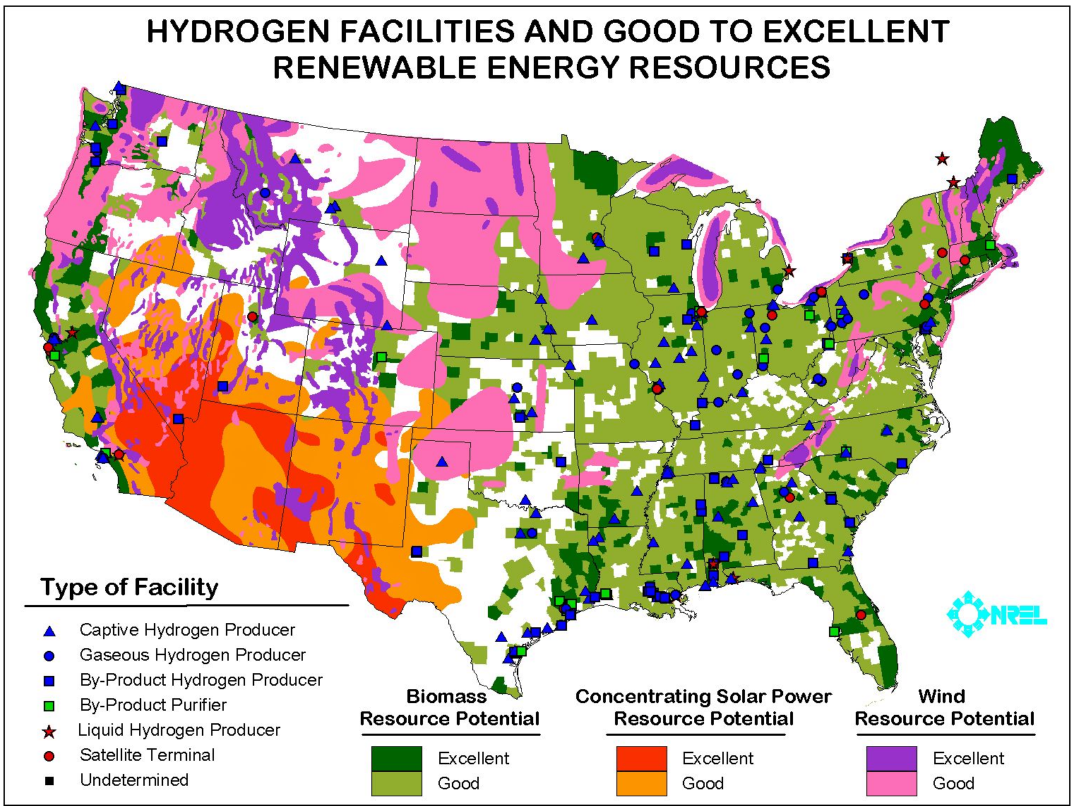



**Figure 7. Hydrogen Facilities and Good to Excellent Renewable Energy Resources**

**Wind electrolysis is likely to be the first economical renewable hydrogen production system**, simply because the cost of energy from wind right now is probably the lowest of the renewable technologies. Figure 7 shows the renewable energy resources for our country including wind, solar and biomass. **Between the wind, solar and biomass resources, we've got the country pretty well covered.** The small circles on the map indicate the current hydrogen production facilities and illustrate that we currently have a small infrastructure in the U.S.

**There are several key reasons for seeking a renewable hydrogen future: energy security, environmental health, and economy for producing jobs locally.**

The first challenge to reaching this future is cost. We need to lower the capital costs, improve processes for purification and separation of hydrogen, increase the efficiency, and look at feedstock, particularly water availability. Distributed generation versus centralized production of electricity and fuels is another major consideration. Delivery, of course, is a huge issue. We also need to look at feedstock flexibility and the match of demand to supply.

Cost is a central concern. The costs of wind electrolysis, biomass gasification, and biomass pyrolysis, on a dollar per kilogram basis (roughly equivalent to dollar per gallon of gasoline), are compared through 2015 in Figure 8. For reference, the costs of electrolysis, with electricity available 6¢ a kilowatt hour versus 17¢, as projected for PV in 2010, are included in the figure.

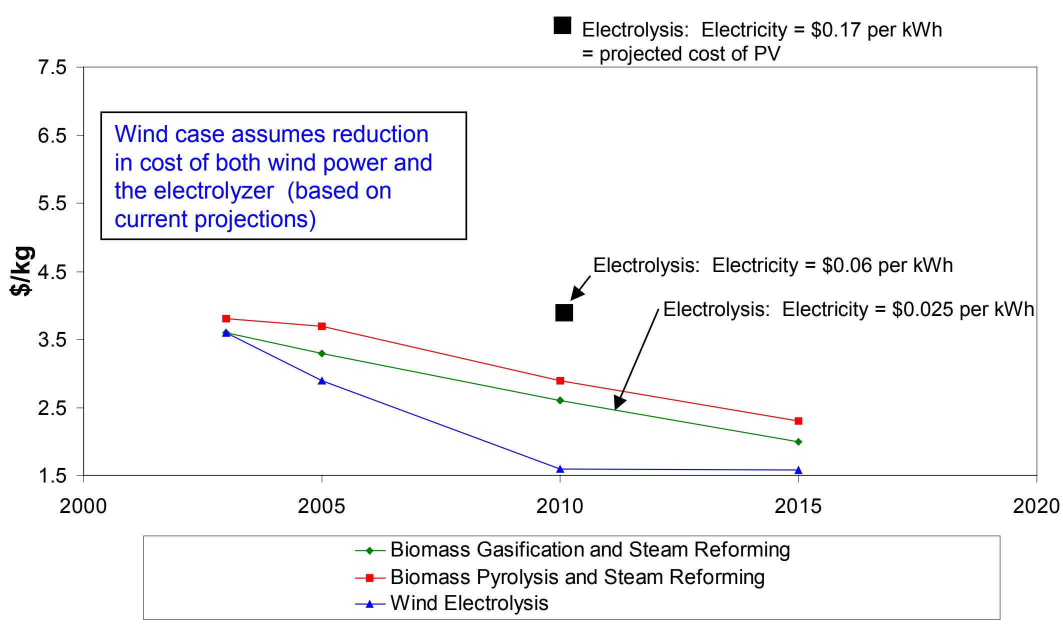



**Figure 8. Hydrogen Production: Mid-Term Opportunities (cost does not include compression, storage or delivery)**

From this analysis, **hydrogen via wind electrolysis appears to be the most economical production method**. This analysis includes the capital cost of the project and the operating costs—the projected lifetime cost to produce hydrogen—but not the costs of compressing hydrogen. The shapes, and probably the order, of those lines would change if all of the storage and delivery costs were considered. We all need to keep that in mind that we will have to be competitive with other apparently low cost options.

Comparing these technologies to future technologies (see Figure 9), such as direct water splitting, illustrates that **even though these technologies are very expensive today, they have the potential to also be cost competitive in the future. Since one of our goals needs to be diversity, we should seriously consider these options.**

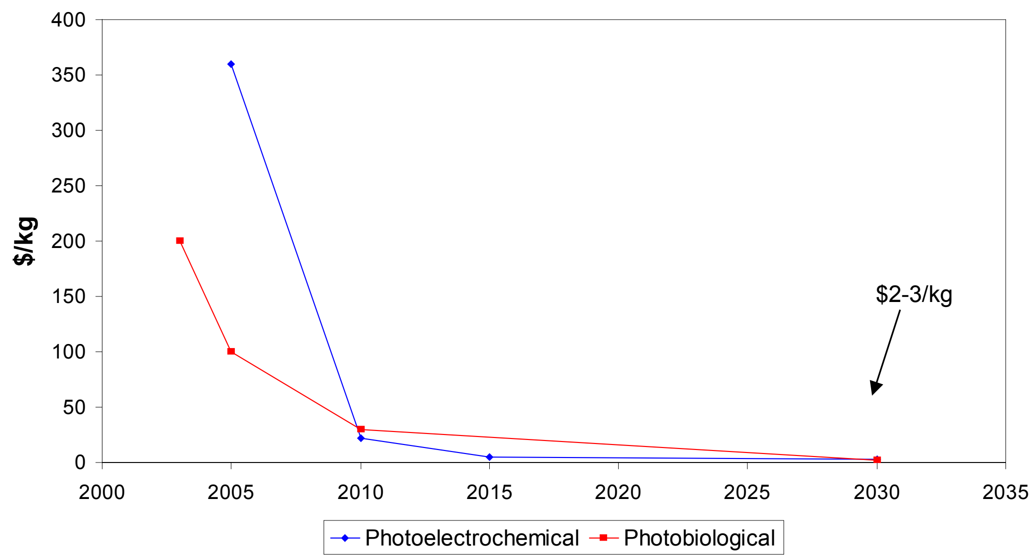



**Figure 9. Hydrogen Production Long-Term R&D: Direct Water Splitting (cost does not include compression, storage or delivery)**

How much of different resources would be needed to supply hydrogen in large amounts? If we want to fuel about half of our current light duty vehicle fleet with hydrogen—that's about 100 million vehicles—and we assume we're using fuel cells, which are twice as efficient as current engines, **we will need 40 million tons of hydrogen a year to fuel those cars. Now to produce 40 million tons of hydrogen, it will either take 95 million tons of natural gas, which would be about a 20% increase over our current consumption; 310 million tons of coal, which is about a 30% increase over current consumption; 400-800 million tons of biomass, which is roughly equal to the residue and waste and some dedicated crops that are currently available; the wind capacity just from North Dakota; or 3,750 square miles of solar panels.**

What is important to us is how we produce the hydrogen and the many issues involved. **We need to consider the external factors** such as carbon production. **We need to figure out how to put a value on those additional benefits. We need to keep in mind that diversity is important for energy security. We also need to consider both distributed and centralized production.** In the end, we will probably end up with a mix of all of these production options.

Susan Hock

### *Chemical – Aldo Steinfeld*

Six thermochemical routes for solar hydrogen production are depicted in Figure 10[29]. Indicated is the chemical source of $H_2$: water for the solar thermolysis and the solar thermochemical cycles, fossil fuels for the solar cracking, a combination of fossil fuels and $H_2O$ for the solar reforming and solar gasification, and a combination of fossil fuels and metal oxides for the solar carbothermic reduction followed by hydrolysis of metals for hydrogen production. All of these routes involve endothermic reactions that make use of concentrated solar radiation as the energy source of high-temperature process heat.

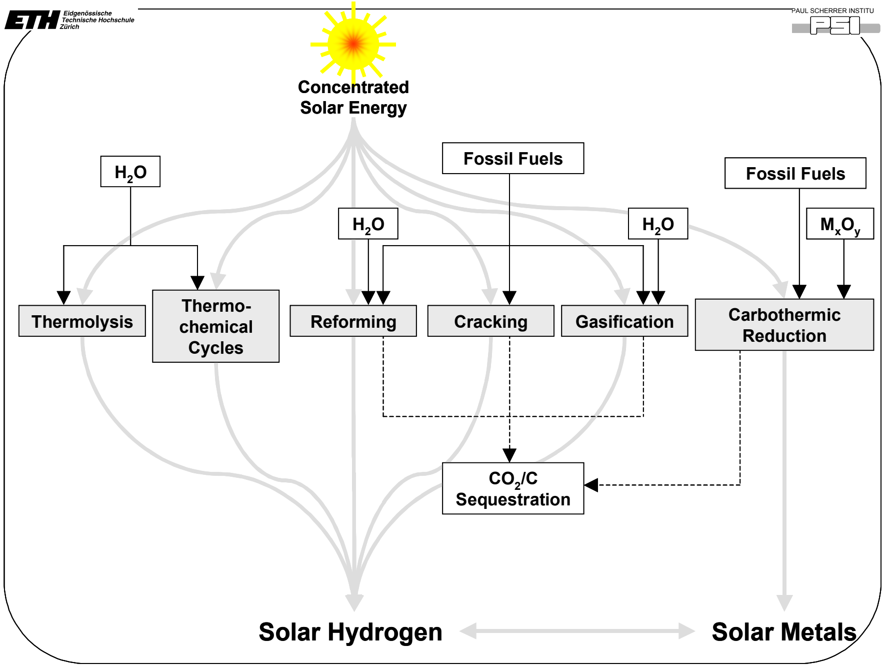



**Figure 10. Thermochemical Routes for Solar Hydrogen Production**

Large-scale concentration of solar energy is mainly based on three optical configurations using parabolic reflectors, namely: trough, tower, and dish systems. **The motivation for following the thermochemical path is its potential for reaching very high exergy conversion efficiencies, exceeding 50%.** *Exergy* efficiency for a solar thermochemical process is the efficiency for converting solar energy into chemical energy. It is given by the ratio of the maximum work (e.g., electrical work) that may be extracted from a solar fuel to the solar energy input for producing such a fuel.

The higher the energy efficiency, the lower is the required solar collection area for producing a given amount of solar $H_2$. Consequently, lower costs are incurred for the solar concentrating system, which usually correspond to half of the total investments for the entire solar chemical plant. Thus, high exergy efficiency implies favorable economic competitiveness.

The single-step thermal dissociation of water is known as water thermolysis. Although conceptually simple, it has been impeded by the need for a high-temperature heat source at above 2500 K to achieve a reasonable degree of dissociation, and by the need for an effective technique for separating $H_2$ and $O_2$ to avoid their recombination. Among the ideas proposed for separating $H_2$ from the products are effusion separation and electrolytic separation. Semi-permeable membranes based on $ZrO_2$ and other high-temperature materials have been tested at above 2500 K, but these ceramics usually fail to withstand the severe thermal shocks that often occur when working under high-flux solar irradiation. Rapid quench, by injecting a cold gas or by expansion in a nozzle, is simple and workable but the quench introduces a significant drop in the exergy efficiency and produces an explosive gas mixture. Furthermore, the very high temperatures demanded by the thermodynamics of the process (e.g. 3000 K for 64% dissociation at 1 bar) pose severe material problems and can lead to significant re-radiation from the reactor, thereby lowering the exergy efficiency.

Water-splitting thermochemical cycles bypass the $H_2/O_2$ separation problem and allow operation at relatively moderate upper temperatures. Previous studies performed on water-splitting thermochemical cycles were mostly characterized by the use of process heat at temperatures below about 1200 K, available from nuclear and other thermal sources. These cycles required multiple steps (more than two) and suffered from inherent inefficiencies associated with heat transfer and product separation at each step. In recent years, significant progress has been made in the development of optical systems for large-scale solar concentration, which are capable of achieving mean solar concentration ratios exceeding 5,000 suns. Such high radiation fluxes, which are needed for the more efficient 2-step thermochemical cycles based on metal oxide redox reactions, allow the conversion of solar energy to thermal reservoirs at 2000 K and above. The first endothermic step is the solar thermal dissociation of the metal oxide to the metal. The second non-solar, exothermic step is the hydrolysis of the metal to form $H_2$ and the corresponding metal oxide. The net reaction is $H_2O = H_2 + 0.5O_2$, but since $H_2$ and $O_2$ are formed in different steps, the need for high-temperature gas separation is thereby eliminated. One of the most favorable candidate metal oxide redox pairs for this 2-step cycle is presumably ZnO/Zn[30].

Processes based on “Solar Upgrade and Decarbonization of Fossil Fuels” can be used to decarbonize fossil fuels via cracking, reforming, or gasification prior to use for power generation. These are high-temperature highly endothermic processes. Using solar energy for process heat offers a three-fold advantage: the discharge of pollutants is avoided, the gaseous products are not contaminated, and the calorific value of the fuel is upgraded by adding solar energy in an amount equal to the enthalpy change of the reaction. These processes offer viable and efficient routes for hydrogen production and $CO_2$ avoidance. **The mix of fossil fuels and solar energy creates a link between today’s fossil-fuel-based technology and tomorrow’s solar chemical technology.** It also builds bridges between present and future energy economies because of the potential for solar energy to become a viable economic path once the cost of energy accounts for the environmental externalities from burning fossil fuels. The transition from fossil fuels to solar hydrogen can occur smoothly, and the lead-time for transferring important solar technology to industry can be reduced.

More detail can be found at these references. [31-33]

***Questions and Comments on Aldo Steineld’s Presentation***

**Harry Braun:** A question on costs. Any ideas on your capital cost assumptions if you put this system into production and correspondingly what would be the cost of the hydrogen?

**Aldo Steinfeld:** Our studies indicate that the cost of solar hydrogen by thermochemical production ranges between 10-15 US cents/kWh (based on its LHV) and, thus, can be competitive with the cost of hydrogen by electrolysis of water using solar-generated electricity. For hybrid solar/fossil fuel based processes, the cost will range between that for 100% solar-based H2 to that for 100% fossil-fuel-based H2. **We are still a factor of two to three over the dirty hydrogen - the hydrogen from fossil fuels. The difference is the price for sustainability, the added price we need to pay for getting the clean hydrogen.**

**Ron Larson:** You are the only person here from Europe and I wonder if you could talk a little bit more about the European approach in general. It’s my understanding that you’re suggesting concentrating solar power is the preferred approach within Europe.

**Aldo Steinfeld:** I don’t know if the solar thermochemical route is the preferred approach in all Europe. It is the approach that Switzerland with partners in the European Union is pursuing: France, Germany, Spain, Israel, and Sweden - this is an international project. **The emphasis of the European Union programs is hydrogen production with CO2-free sources of energy.** There is a nuclear piece as well. But hydrogen production using renewable energy sources (solar, wind, biomass, etc.) is strongly supported.

### *CSP/Electrolysis and Thermal – Dale Rogers*

Disruptive forces, such as deregulation, environmental concerns and energy security, are creating new energy market opportunities. Rocketdyne is leveraging core competencies to take advantage of these with a "Clean & Green" emphasis. We believe that molten salt solar power towers are a viable option for hydrogen production. The technology has been successfully demonstrated and is ready for market entry. Trade studies are needed but CSP appears to be a good fit for hydrogen production.

### *Algae – Ralph Overend*

Algae are extraordinary adaptable microorganisms. They will grow in extremely saline environments and extremely hot environments such as in Yellowstone Park. They have a distinct performance advantage over terrestrial plants. There are as many as 40,000 species. They don't have tree trunks. They don't have leaves. They don't have roots. In other words, they're very efficient photosynthetic machines but they don't make a lot of biomass. So they divert very little of the solar energy that was captured from the sun using $CO_2$ and water into biomass. In fact, if you look at the ocean, about half of the world's photosynthesis capture of $CO_2$ takes place in the oceans and the other half takes place on the land. **The biomass in the oceans is extremely small, which means that these microorganisms have very high turn over rates and are very efficient.** Based on measured growth rates, the rate of movement of solar energy through these microorganisms is between ten and 100 times that of terrestrial biomass. In the algae systems, protein synthesis as high as nearly 100 grams per square meter per day have been reached. For comparison, soy bean plants produce about two grams per square meter per day.

In the 1970's there was a major attempt to grow macro algae—giant algae such as kelp—in the open ocean. During the 1980's there was a major program that explored oil-bearing species from the Dead Sea in Israel as a means of making biodiesel. Today several biological hydrogen production systems using microorganisms, anaerobic digestion processes, and the use of green algae are under investigation. There is a lot of promise in the algae system. The algal hydrogen photoproduction system is illustrated in Figure 11. The goal is to develop a cost-effective system for algal hydrogen production that is renewable, stable and self-sustaining, efficient, and clean. This is essentially a solar technology, which is like PV. It will require a large surface area to produce a significant amount of energy. The reactor, which is shallow, maintains the right temperatures for the growth of the algae and has a barrier that prevents the oxygen in the air from reaching the system.

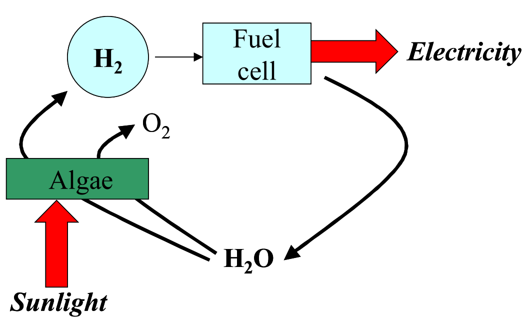



**Figure 11. Hydrogen Production by Algae**

**The projected costs are certainly less than $10 a kilogram. The drivers that are going to affect getting to that cost are the depth of the pond that captures the solar energy and the amount of light penetration with depth.** There are still some significant engineering challenges facing this technology, but the productivity is increasing.

## Future Research Needs

This session addressed research needs for advancing renewable hydrogen.

- Moderator: Brad Collins, Executive Director, American Solar Energy Society
- David Garman, Assistant Secretary, Energy Efficiency and Renewable Energy, US Department of Energy
- Stan Bull, Associate Director for Science and Technology, National Renewable Energy Laboratory

### *David Garman*

**Is hydrogen is a national security issue or an environmental issue? In fact it's both** and you don't need to look beyond the words of the President himself to answer that question. The environmental benefits of hydrogen are something that is very much on the mind of the President. He also has discussed the energy security aspects and changing dependence on foreign sources of energy. In addition, **the U.S. currently has a large amount of energy coming from gas, coal and petroleum--the energy resources that concern us because of their emissions.**


David Garman

Some of the future possibilities for moving forward with hydrogen include the "Go–Sooner" scooter by Ovonics, a hydrogen ICE vehicle that could replace two-wheel scooters. For example, in New Delhi or Bangkok where two-wheel scooters are endemic, urban air quality is a critical problem that could be addressed with these new scooters. In other areas, as part of the Freedom Car Partnership, goals for performance in ICEs using hydrogen have been defined. At the last auto show, Ford displayed their model U, a concept vehicle to burn hydrogen in an ICE. Of course, the issue of hydrogen storage on board the vehicle still needs to be addressed.

Energy sources that emit air pollutants have costs that aren't always reflected in market prices. For example, in the case of coal**, if we added in the cost due to the estimated 15,000 premature mortalities from chronic obstructed pulmonary disease**

**attributed to coal, the cost of electricity from coal would increase by several pennies on a kilowatt-hour basis.**

Research into advanced renewable hydrogen technologies is well underway. For example, using the energy in a photon to split water and make hydrogen directly is viewed as a good long-term option, although the costs right now are quite high. **There also is a pretty good argument for concentrating solar technology. That is why EERE has been working to get that technology back on the map.**

***Stan Bull***

When you think about a hydrogen economy, it is linked to the electricity system and/or a combined heat and power system, which would include generation of electricity. These systems play off each other - particularly with regard to economic evaluations and setting priorities for research. **Research opportunities are all targeted toward lower cost, higher efficiency, and longer durability**—the three key elements for renewable hydrogen production success down the road.

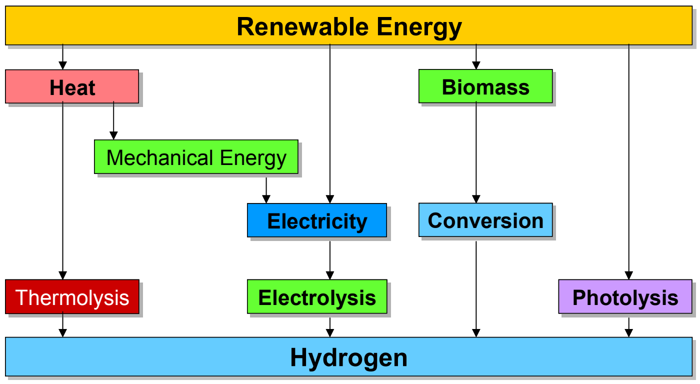



**Figure 12. Renewable Paths to Hydrogen**

The idea behind water splitting is to directly produce hydrogen and oxygen from water and sunlight. Using advanced photoelectrochemical (PEC) technologies, **today in the laboratory, we can achieve 12.4% conversion efficiency[34] for solar energy to hydrogen.** This is an exciting achievement and is the best in the world so far. More research is needed to increase the lifetime of the PEC device, which is currently on the order of hours—not years.

Third-generation solar cells are another area of research. Building on first and second generation advances, third generation devices generally have theoretical limits of 32% efficiency. That's the maximum we can do with the best kind of system we can put together. To get higher efficiencies, we need to take advantage of quantum dots, which have the potential to reach 67%, and maybe even higher, efficiency. The costs and efficiencies of these systems are compared in Figure 13.

## I. 1st Generation

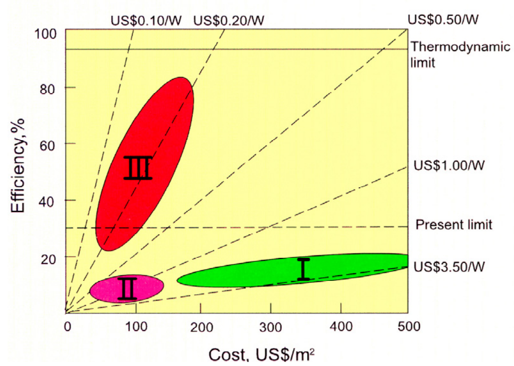
- Single crystal Si
- Poly-grain Si

## II. 2nd Generation (Polycrystalline Thin Film)

- Amorphous Si
- Thin film Si
- $CuInSe_2$
- CdTe
- Dye-sensitized PV

## III. 3rd Generation ($n_{theor}$>31%; Queisser-Schockley limit)

- Hot electron converters
- Impact ionization cells
- Mid-band PV




Region III indicates efficiencies higher than previous theoretical limits, at lower costs, made possible by nanostructures such as quantum dots

**Figure 13. Hydrogen via 3rd Generation Solar Cells**

Carbon nanotubes are a promising area for hydrogen storage. **With very modest changes, either in temperature or in pressure, the nanotubes will absorb hydrogen or release hydrogen, at around room temperature.** In the laboratory, thimble-size amounts of this material, capable of storing 8% weight percent hydrogen, have been produced. Current research is working to resolve problems with consistency of production of the material and to develop a process for producing it in a mass quantity. In concept we envision a tank, much like a conventional gas tank, that's filled with these little carbon fibers.

Computers have become so powerful; we can simulate complex processes, which means we can be more efficient in exploring new ideas and conducting initial investigations. Eventually demonstrations are required to verify the results of these computer models and prove the technology in real-world applications.

As we move forward, **we need to be looking across the whole system.** Each of the individual areas are vital as we go about planning and exploring future research needs, and making decisions on those needs. For example, we might explore opportunities for demonstration of wind to hydrogen or solar in a local setting to produce hydrogen in conjunction with a mass transit system.

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## KEYNOTE ADDRESS

The keynote explored fundamental concepts of building the renewable hydrogen economy.

- Introduction: Maury Albertson, Hydrogen Now
- Building the Wind/Hydrogen Economy: Lester Brown, President, Earth Policy Institute

Brad Collins and Maury Albertson

### Building the Wind/Hydrogen Economy – Lester Brown

Is the environment part of the economy? Or is the economy part of the environment? **If we accept the idea that the economy is part of the environment, then it follows that the design of the economy must be compatible with the environment.** Right now it is not. It is a highly stressed relationship and becoming increasingly so each year as the economy expands. We read about the stresses in the daily newspapers. Collapsing fisheries. Shrinking forests. Expanding deserts. Falling water tables. Rising $CO_2$ levels. Rising temperature. Ice melting. Soil erosion. Disappearing species. These are all manifestations of the stress between the global economy and the earth's ecosystem.[35]

Now many of us have been convinced by these environmental trends of the need to restructure the world economy. But we're still a minority. Some people have been convinced by what's happening in China. The Chinese economy, as you know, has been the fastest growing economy in the world since 1980. China is telescoping history, helping us to understand what happens when large numbers of poor people rapidly become more affluent.[36]

**What would happen if China were to use gasoline at the same rate that we do. China would need 80 million barrels of oil a day. The world is currently producing only 76 million and probably will never produce much more than we now are.** Or consider paper consumption. If paper consumption in China were raised to the U.S. level, China would need more paper than the world produces. **The bottom line is that the western industrial economic model is not going to work for China** and if it doesn't work for China it's not going to work for India, which now also has over a billion people. And it won't work for the other two billion people in the developing countries either. In the long run, in an increasingly integrated global economy, it will not work for us either. That's the bottom line. That's the context for the issues that are being dealt with in this Forum.[37]

**The fossil fuel-based, automobile centered, throw-away economy is not a viable model for the world over the long term.** We now have to think about shifting from fossil fuels to renewable sources of energy; from automobile-centered urban transport systems to rail-centered and bicycle-centered systems. That doesn't mean we'll eliminate cars but they will not be the dominant mode of transportation in cities as they are today. It means going beyond the throw-away economy toward the reuse, recycle economy.

There have been a number of proposals recently that have begun to catch the spirit of the needed restructuring. For example, we had a proposal from the Suzuki Foundation and the Climate Action Network in Canada to reduce carbon emissions 50% by 2030 and to do it only in ways that were profitable. Dupont cut greenhouse emissions by 65% since 1990. Interface, the industrial carpet manufacturing company based in Georgia, cut carbon emissions in its Canadian facility by 64% and did it in ways that made money. The Ontario Clean Air Alliance is proposing that the five coal-fired power plants in Ontario be phased out and all three major political parties have agreed to do this[38]

If you look around the world, things are beginning to happen and I think this process is going to be driven by events over the next few years. I've been asking myself what sort of wake-up calls might we expect that would take things to another level and reinforce our interest in clean hydrogen. One such wake-up call could come on the food front. Last year the world's farmers fell about 80 million tons short of world consumption. That's about 4%. The year before, they were short by 29 million tons. The year before that, by 30 million tons. So we've had three consecutive years now in which production did not meet consumption. We satisfied the demand by drawing down stocks, which means that world grain stocks are now at the lowest level in 20 or 30 years.[39]

Now the question is: can farmers catch up? Can they dig their way out of this hole? In the past they always have. Prices would go up. They would expand the planted area. Use more fertilizer, more irrigation, etc. But farmers are facing two new challenges now. One is rising temperatures. The other is falling water tables. **The generation of farmers now on the land is likely going to be facing higher temperatures than any generation of farmers since agriculture began.** I think we forget that agriculture, as it exists today, has evolved over a period of 11,000 years with rather remarkable climate stability. Now suddenly that's beginning to change. You only have to look at the temperature chart and see the rise since 1980 to understand the dimensions of this change.[40]

We're also now beginning to realize that crop yields are more sensitive to temperature increases than we have thought. The conclusion of the International Rice Research Institute in the Philippines and the U.S. Department of Agriculture, Agricultural Research Service, is that each one degree Celsius rise in temperature above the norm during the growing season reduces crop yields by 10%. Now we look at global average temperatures and we don't see any great increases. But keep in mind that the increases will be very uneven over the earth's surfaces. Temperature increases much more over land than over the ocean and much more at the higher latitudes than in the equatorial regions. You see the evidence of this in Alaska, for example, where the temperature has gone up 3-7 degrees over the last several decades.[41]

A few weeks ago, two scientists at the Carnegie Institution published an article in Science, which looked at the effect of temperature on corn and soybean yields in the United States, using data for some 600 counties for the last 17 years. They isolated the effects of temperature from rainfall. **Their conclusion is that each 1 degree rise in temperature Celsius reduces the yields of both corn and soybeans by 17%.** This is an even stronger indication of an even stronger link between temperature and yield.[42]

We can say the three warmest years on record have come in the last five years. With that, we have falling water tables. Irrigation problems go back 6,000 years. Falling water tables have only begun as an issue in the last half-century since we've had diesel and powerful electrically driven pumps. What's happened is the world demand for food has gone up. Countries have turned more and more to the use of underground water for irrigation -. countries like China and India in particular. **We are now over-pumping on a scale that's almost difficult to imagine.**

What they're doing is creating a food bubble economy. What I mean is that over-pumping is a technique is used to expand current production but it almost guarantees a future decline in production when the aquifer's depleted - at which time the rate of pumping must be reduced to the rate of recharge.

This creates a fascinating geopolitical situation because China, with 1.3 billion consumers who have an $80 billion dollar trade surplus to the United States, coming into our market and competing with us for our grain is likely to raise grain prices and food prices. At that point, the Chinese will realize that they are no longer self sufficient - that they are dependent on the outside world for part of their food supply and we will realize that, like it or not, we are sharing water scarcity and food shortages with China. It will be a new world.[43]

We have a stake today in a politically stable China. It is the Chinese economy that is not only the engine for the Asian economy today. It is also the only large economy in the world that's really hitting on all fours. The world is very much dependent on the rapid growth of the Chinese economy to keep things going. I could talk about other scenarios that could wake us up as well like dramatic changes in the Arctic climate and Greenland beginning to melt big time.

What I would like to talk about is what I see in looking at the new energy economy. **My guess is that we should be headed toward a wind-hydrogen economy.** As you all know, our wind electric generation in the last seven years—1995 through 2002—has been growing at 32% per year on average. In Europe, Denmark is getting 18% of its electricity from wind and in the northern-most state in Germany, it's 28%. In the industrial providence of Navarra in Spain, 22%, we're really beginning to see wind become an established source of energy.[44]

**There are several reasons why wind power is growing so fast. It's abundant, cheap, clean, climate benign, inexhaustible, and widely distributed. No other energy source has those attributes.** Estimates for China indicate that China can double its current electricity generation from wind alone. Europe, which is densely populated, can satisfy all of its electricity needs from offshore installations. In this country, North Dakota, Kansas and Texas have enough harnessable wind energy to satisfy national electricity needs.[45]

Wind is cheap. Fifteen years ago in this country it cost 38¢ a kilowatt-hour. Now in high wind sites it's down to 4¢. Some recent contracts for a long-term supply are at 3¢ a kilowatt-hour. With each doubling of world capacity, costs drop another 15%. So we're looking down the road at wind generated electricity that is going to be really cheap.[46]

The economics are interesting at the grass roots level. A farmer in Northern Iowa, who leases a quarter acre of land to the local utility to site a large advanced design wind turbine, gets $2000 a year in royalties. That same quarter acre produces $100 worth of corn. **One of the exciting things about wind power is that much of the money spent on electricity that comes from local wind farms stays in the local community. So there's the economic development potential that now comes with wind energy**.[47]


Lester Brown

Once we get cheap electricity, then we have the option of electrolyzing water to produce hydrogen. Hydrogen is the fuel choice for fuel cells. Every major automobile manufacturer is now working on automobiles with fuel cell engines. So this opens up a vast new area. **We're looking at a future where farmers and ranchers in this country who own most of the wind rights could one day be satisfying not only most of the country's electricity needs, but also supplying much of the fuel for the country's automobiles as well. It's a new world.**

One of the interesting things about energy is that during the last century the global energy economy became increasingly globalized. The world became progressively more dependent on oil and on one region of the world for its energy. **Now as we begin moving toward renewables--wind, solar cells, and so forth—we're seeing not the globalization of the energy economy but the localization of the energy economy. As this century progresses we will be depending more and more on local sources of energy.**

Now one of the big questions is how do we get from here to there. That's economics, that's engineering and a whole range of other issues, many of which have been discussed here at this Forum. It seems to me that we have to think about restructuring the energy economy to get the market to tell the truth, because right now the market does not tell the truth. When we buy a gallon of gasoline, we pay for the cost of getting the oil out of the ground, getting it to a refinery, refining it into gasoline, and getting the gasoline to the local service station. We do not pay the cost of the air pollution impacts like respiratory illnesses. We don't pay the cost of damage from acid rain. We don't pay the cost of climate disruption. **We've got to think about how to get the market to tell the truth.**

**What is the cost to society of burning a gallon of gasoline?** Is it likely to be more or less than the cost to society of smoking a pack of cigarettes? The answer is we don't know. The World Bank three years ago published a map of Bangladesh with a meter rise in sea level. One meter is entirely within range of the projected sea level rise for this century according to the Intergovernmental Panel on Climate Change (IPCC). Based on more recent data on ice melting; it could go well beyond that in this century. One meter rise in sea level in Bangladesh loses half of its rice land. This is a country of 140 million people. A meter rise in sea level also would probably displace at least 40 million people. What's the cost of relocating 40 million people? Do you relocate them all internally? This is one of the most densely populated countries in the world. Or do you move them internationally to less densely populated areas like Australia, Brazil, the United States, and Canada? **These costs are almost incalculable when you begin thinking about them.**[48]

The obvious way to get the market to tell the truth is to calculate the indirect costs and incorporate them in the form of a tax, lowering income taxes and raising taxes on environmentally destructive activities like car emissions. This then begins to get **the systemic change because anyone who uses energy, whether it's consumers, or corporations, or government policy makers, will be affected by the real cost of burning fossil fuels**. We know how to do this. We know how to restructure the tax systems. It's not a mystery. Some countries are already doing it.

**We also need to think about restructuring the subsidies. The World Bank says $210 billion of subsidies go to fossil fuel use. Imagine what would happen to solar cells and wind and geothermal if we shifted that $210 billion to renewables** (e.g., http://www.gci.ch/GreenCrossPrograms/rio/articles/uspoliticians.html). We'd really begin to pick up the pace. **If you think about it, it makes no sense at all to subsidize fossil fuels.**[49]

I'll wrap up with a quote from Øystein Dahle, who was for many years Exxon's Vice President for Norway and the North Sea. Øystein ended up taking early retirement because he and Exxon were getting further and further apart on the issues. He said socialism collapsed because it did not allow the market to tell the economic truths. **Capitalism may collapse because it does not allow the market to tell the ecological truth.**

## Discussion

**Julian Dolly:** Where is natural gas going to come from for a hydrogen economy in the near term?

**Lester Brown:** I don't know the answer to that question. But I do know that more and more people are turning to natural gas because it is clean and it is more carbon efficient. The more seriously that problems come on the climate and air pollution front, the more pressure there will be to move from coal to natural gas in power plants, for example. That's a trend that's well underway in many countries in the world. **I don't know what will happen when it becomes clear that that's a short run solution.**

**David Freeman:** Many of us have hoped that we get the prices right. But with $4 and $5 a gallon gasoline in Europe for decades now, they haven't thought about the hydrogen economy. I wonder if the numbers aren't the turf of the economist and values are the turf of the human environment. I don't think that getting the numbers right will have a profound impact on consumption. We haven't seen any fundamental new technologies develop because of price. I would suggest that you put a lot more emphasis on educating the people of this planet to the fact that the hydrogen economy is a here and now possibility. **Democracy doesn't function without an educated population - and we're hydrogen illiterate.** All the propaganda coming out of Washington, including what we heard earlier, still just talks about the fuel cell. But the hydrogen economy is much more fundamental than the fuel cell. The internal combustion engine can run on hydrogen. We need to get started now. I don't think $4 a gallon gasoline would make it happen. It didn't in Europe. So while it would be nice to have the prices right, I think we've got to be more demanding in what we ask for. I wonder if you don't agree with that?

**Lester Brown:** I think what the $4 and $5 a gallon gasoline in Europe and in Japan did do was to lead to much more energy efficient automobiles. If in this country, prices were to go up to the European or Japanese levels, I think we would see a consumption response to that. The adjustment of Europe and Japan to $4 to $5 a gallon gasoline was more efficient automobiles and better public transportation. Over the last decade we've seen exciting advances in wind turbine design and the continuing evolution of the fuel cell. **It is not just that the technologies are becoming available but that we can begin to see the economics starting to work out. We're not too many years away from realizing how enormously economically disruptive climate change is going to be. I think that will provide momentum.**

## ECONOMICS

This session focused on the economics of renewable hydrogen.

- Introduction to Issues & Moderator: Harry Braun, Chairman and CEO, Sustainable Partners, Inc
- Henry Kelly, Chairman, Federation of American Scientists
- Margaret Mann, Senior Chemical Process Engineer, National Renewable Energy Laboratory
- Sivan Kartha, Tellus Institute

### *Introduction to Issues & Moderator – Harry Braun*

**Hydrogen is the only "universal fuel" that can run everything from space ships, to a Coleman stove on a mountain top, to existing appliances in homes.** The technology is already here. **Hydrogen can power every existing vehicle on the road.** That means SUVs, hybrids, or any remaining Model T Fords. The capability is not new. Rudolph Erren was a German engineer who in the 1930's developed a simple fuel injection system for internal combustion engines that cost a few hundred dollars a vehicle. You could flip a switch and go back and forth from gasoline to hydrogen. This is 1930s-era technology.

**Liquid hydrogen can be handled by virtually anyone. It's safer than gasoline and other hydrocarbon fuels, and it gives the vehicle the same performance and ranges as gasoline.** This has been validated by BMW, which has been focusing on liquid hydrogen fuel cars with IC engines for the past 25 years.

It's cost that's holding up the hydrogen economy. For example, according to GM, fuel cells will cost \$50,000-\$100,000 per vehicle even in high-volume production—and that is just the fuel cell stack. Studies done by the American Academy for the Advancement of Sciences suggest that world platinum production would have to be increased by a factor of thirty in order to accommodate the fuel cells. Platinum is already an expensive metal; it will get more expensive when you start consuming it on such a scale. In the future, when people drive up to the gas station and the hydrogen pump is \$3/gallon and the gasoline is \$2/gallon, most people will buy the gasoline. We need to make sure that doesn't happen.

Wind-powered hydrogen production systems and passage of a Fair Accounting Act could do it. If we assume that a wind turbine puts out an average of a megawatt and works about one-third of the time, 10 to 12 million of these power conversion units are needed to make 100 quads of energy to run the whole country. All those wind turbines could be built in just a couple of years once the tooling is in place, because they are similar to an automobile from a manufacturing perspective.

The big problems with wind today are that the wind is not dispatchable and it is intermittent. **The other big issue is getting the electricity to market when most of**

**the transmission lines are saturated. Liquid hydrogen in pipelines solves both those problems at once.**

So how is this all going to happen? This is not a technical issue. It will take political leadership. **If you want to have a significant impact on oil imports, in fact if you want to eliminate them, if you want a significant impact on the air quality, and if you want to employ about 10 million Americans, then this transition is the way to do it.**

We need a hydrogen production board that would be similar to the War Production Board set up by President Roosevelt in World War II. Everybody—from the energy to the automotive, aerospace, pipelines and ship sectors—was included at the table and they were all working on the same timeframe and working together in cooperation. We need that now.

The Phoenix Project (phoenixproject.net) is a plan to mass-produce wind-powered hydrogen production systems with wartime speed (by 2010) and simply modify every existing vehicle (including aircraft) to use hydrogen fuel.

Factoring in the external costs of energy will level the playing field. According to a Scientific American article that was published a number of years ago, **at least $1/gallon carbon tax would be required if you were trying to factor in the basic military, healthcare, and related external costs. If you factored in climate change, that number would be even higher.**

The purpose of the Fair Accounting Act legislation is to factor in these external costs. This proposed legislation needs to be passed by the Congress. It will do two things. First, it will stop the $3 billion/week in subsides to the fossil and nuclear industry. It will take that money instead and put it into the renewables that can make our country energy independent without all the environmental downsides. Because those wind machines are like cars that can be mass-produced, the transition can happen quickly. Second, the Fair Accounting Act would impose a $1/gallon carbon tax on gasoline. It would be a temporary tax because within five years the U.S. would be off of gasoline and the carbon tax would go away. In the meantime, cars would need to be modified, and oil and other energy companies would have the necessary financial incentive to become solar hydrogen companies. A tax incentive strategy could give vehicle owners at least a 50% tax credit on the vehicle conversion kit, so that half of the cost of the vehicle conversion would be picked up on a one-time basis. With that kind of financial incentive, the oil companies, not taxpayers, will make the needed $6 trillion investment and within five years we'll have shifted over to hydrogen.

***Henry Kelly***

**Hydrogen doesn't make any economic sense in the next twenty or thirty years without increasing the price of the competing fuels or subsidizing hydrogen.** The possibility of a doubling world population and the fact that the per capita consumption worldwide is increasing by a factor of two or three will create a colossal increase in demand for energy services. The overwhelming problem is personal vehicles. New sources and new ways to transport all of these people will be needed; this is where hydrogen comes in.

Where do you get the hydrogen? The Intergovernmental Panel on Climate Change (IPCC) Business-as-Usual (BAU) forecast shows huge increases in coal and biomass here as potential resources. People talk about biomass as an attractive way to produce hydrogen, but the problem here is that the resource worldwide is not unlimited. Another possibility is electrolysis, but to be a cost effective option, the cost of electricity must be 4¢/kilowatt-hour or less. Wind is a terrific way of making electricity and wind can get close to, or even a bit below, that target. Nuclear electric is probably not going to get anywhere close to that. There are many ways to generate electricity but making electrolytic hydrogen just doesn't seem to pass the economic hurdle.

There are many different ways to use hydrogen in personal vehicles, including simply putting it into diesel engines or gasoline engines. That's not a bad way to do it. In fact the diesel cycle is an extremely efficient cycle. One of the big challenges right now for putting hydrogen into our diesel or auto cycles is meeting the new NOx emissions standards.

One problem with the current U.S. program is that **we are really not integrating what we're doing domestically with a very robust international program.** In particular, we're not helping focus on some of the most explosive growing areas of demand for transportation throughout the world. Another problem is that the total investment we're making across the board in this entire portfolio is too low and may not be focused on the areas that make the most sense. In the case of hydrogen, we need to focus both on near-term investments and a sensible transition strategy.

Even with the most promising assumptions about the future costs, it may be hard to beat gasoline at $1.50/gallon. Without regulations, incentives, or taxes, hydrogen is going to have a tough time, even if hydrogen research and development efforts pay off over 20 years.

***Margaret Mann***

**The economics of a renewable hydrogen system involve production, as well as resources, production, delivery, storage, and end-use of hydrogen.** NREL has analyzed biomass, PV electrolysis, and wind electrolysis hydrogen systems, as well as more advanced technologies, such as some of the longer-term photolysis technologies, concentrating solar power, etc.

Delivery costs and the system that provides the fuel are part of the system. Today we make a lot of our hydrogen from natural gas. The cost depends on how the hydrogen is delivered and stored. Small users, for example, usually receive compressed gas via tube trailer delivery. According to the February 24th edition of the Chemical Marketing

Reporter, the cost of this hydrogen has ranged from about $5.3 – $11.00/kilogram over the last five years. Over the last few years there's been a steady upward trend that generally tracks the increases in the cost of natural gas.

In the captive hydrogen market, because there are no compression or storage requirements, the total costs are lower. If natural gas costs $3.50/million Btu, hydrogen costs about $1.40/kilogram. Even if the natural gas were to cost $5.00/million Btu, our cost will still stay below $2.00/kilogram of hydrogen. That's because there are fixed costs involved in the production process; the plant is already in the ground and labor costs are not going to increase dramatically. Thus, even as natural gas prices rise, as expected, dramatic increases in hydrogen's competitive price won't be seen until significant new capacity is required.

As illustrated in Figure 14, over the last 20 years, significant cost reductions have been made in renewable electricity generation technologies. Further cost reductions are projected for the next 20 years. By using these same technologies to produce hydrogen, we get to take advantage of the cost reductions that have taken place in the past and those expected to take place in the future.

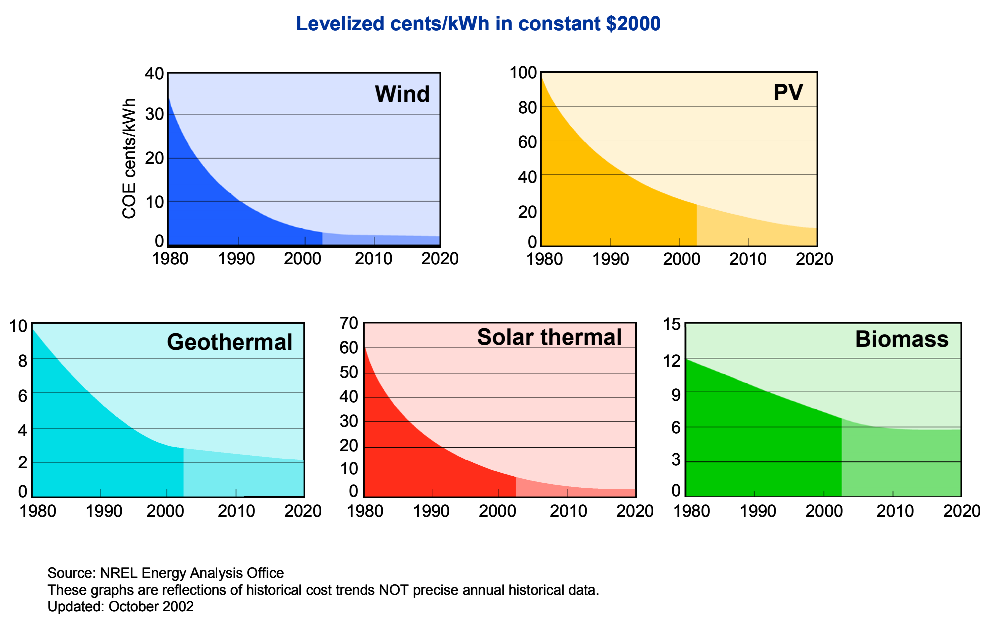



**Figure 14. The Cost of Renewable Energy**

Energy security is an important reason to use renewable energy. **We know that we have enough renewable resources throughout the United States to meet the energy needs of the country as a whole.** By using renewable resources, we can reduce the amount of petroleum we consume and import. Generally for renewables, **if we use 25 kilograms of hydrogen, we displace one barrel of oil.**

In terms of global climate change impacts, **we reduce our greenhouse gas emissions by approximately 3 kilograms of $CO_2$ equivalent per kilogram of hydrogen produced.**

Is water an issue when it comes to hydrogen? Assuming 12,000 miles per year and 60 miles per kilogram of hydrogen, a fuel cell car will need between about three and four gallons of water per day. These are life cycle calculations so they include upstream water usage for manufacturing the plant or the wind turbine, as well as the water usage during the hydrogen production phase. Wind electrolysis uses more water than steam methane reforming, partly because steam methane reforming produces half of its hydrogen from the feedstock itself, whereas water is the only source of the hydrogen in wind electrolysis. Based on the amount of water that's reported to be available throughout the world, the percentage that might be used for hydrogen production can be estimated. In the U.S., four gallons per day per car represents about one-half of one percent. **Even in very water stressed regions of the world, like Northern Africa, four gallons amounts to less than 1% of the water used in those regions.** It's also important to recognize that water is used in the current transportation and energy systems. In power plant systems, we use about a half a gallon of water per kilowatt-hour. **So if we were to transition into hydrogen, we would displace the amount of water that's currently used in today's energy systems.** Something we really need to keep in mind, though, is that these systems are already showing big signs of stress throughout the world. This is just one more piece that could add to that stress.

Figure 4 (page 13) shows the amount of biomass that could be available in 2020. These are cumulative supplies including urban residues, energy crops, forest residues and agricultural residues. At a price of about $3 per gigajoule, about 30 teragrams of hydrogen per year could be produced; that would be enough hydrogen to fuel about 40% of our light duty vehicle fleet. In addition to the fact that a significant amount of hydrogen could be produced from biomass, it's also a relatively low-cost source of renewable hydrogen in the near term. Part of this is due to the dispatchability of biomass, which means that you can produce the hydrogen when you need it. This means that storage costs for biomass-based systems will be lower than for systems using renewable resources such as sunlight and wind, which suffer from a time mismatch between demand and resource availability. On the other hand, wind and solar electrolysis technologies have the advantage of being able to interact with the grid. Another reason that biomass is a good near-term opportunity for hydrogen is that a process called co-reforming can be used to gasify the biomass and produce a gas that could be reformed with natural gas in existing steam methane reforming facilities. This might be a way to quickly introduce renewable hydrogen into a developing hydrogen economy.

While biomass can play an important role in producing renewable hydrogen, wind and solar electrolysis are necessary for meeting all of our energy demands. In terms of solar resources, we don't need that much area to produce all the electricity that the U.S. needs from PV. In terms of PV electrolysis, we could use a small area in New Mexico to produce enough hydrogen for 200 million fuel cell vehicles. In terms of wind energy, our current installed capacity is about 4 gigawatts. The potential installed capacity using just Class Four resources is over 3,000 gigawatts. **Of that we need about 1,100 gigawatts to produce enough hydrogen for all of our light duty fleet in this country.** So we can clearly say there are enough resources available.

What will it cost us? Opportunities for reducing the cost of hydrogen production from wind and PV electrolysis were identified by analyzing a series of possible scenarios. The results are summarized in Figure 15.

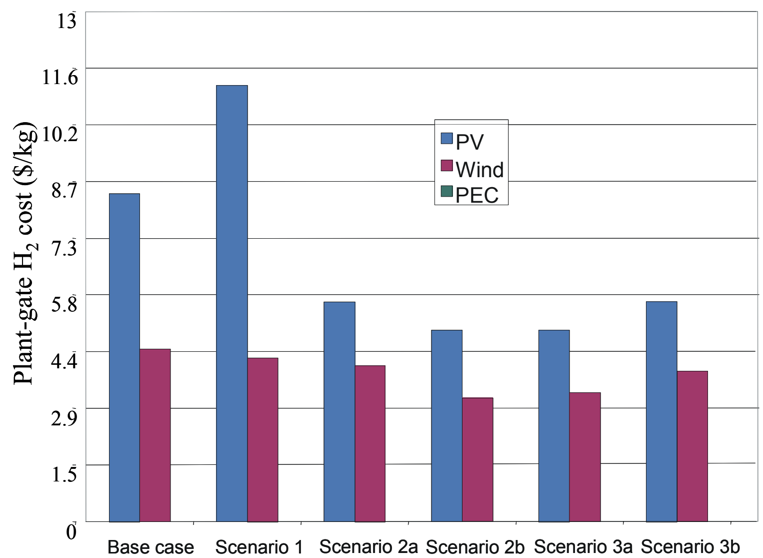



**Figure 15. Grid-Tied PV and Wind Electrolysis**

Scenario 1 looked at what would happen if the electricity is sold as a co-product during on-peak periods. In this case, the energy is used during non-peak periods to produce hydrogen, or only when the renewables are operating (see Figure 16).

In 2A just enough energy is purchased to baseload the electrolyzer. We want to avoid buying this expensive piece of equipment and use it only part-time to produce the saleable product (see Figure 17). Scenario 2A maximizes the on-stream time of the electrolyzer. In 2B, non-peak energy is purchased from the grid only when the renewable isn't operating. In this case, hydrogen is being produced during all non-peak hours and on-peak hours when the renewable is operating (see Figure 18).

In scenario 3A, the hydrogen production system is decoupled from electrolysis. In this case, we send the electricity over the grid; we're wheeling the non-peak energy over the grid and producing hydrogen only during non-peak hours (see Figure 19).

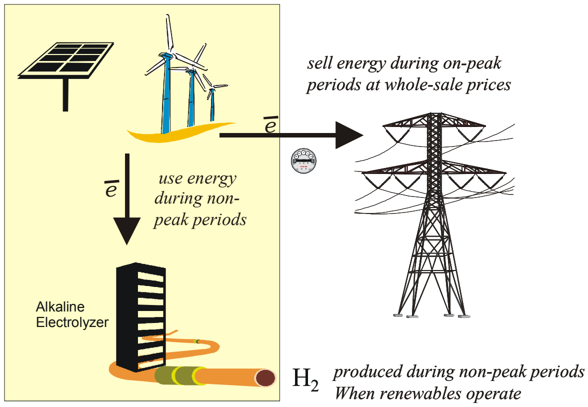



**Figure 16. Scenario 1: Electricity Sold as Co-product during On-Peak Periods**

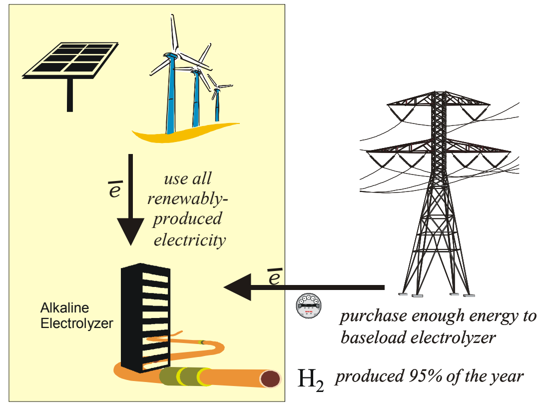



**Figure 17. Scenario 2A: Hydrogen Produced from Renewable Electricity Plus Enough Grid Electricity to Baseload Electrolyzer**

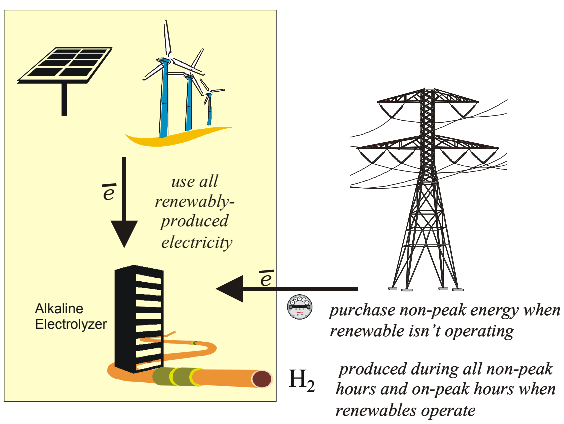



**Figure 18. Scenario 2B: Hydrogen Produced from Renewable Electricity Plus Only Non-Peak Grid Electricity**

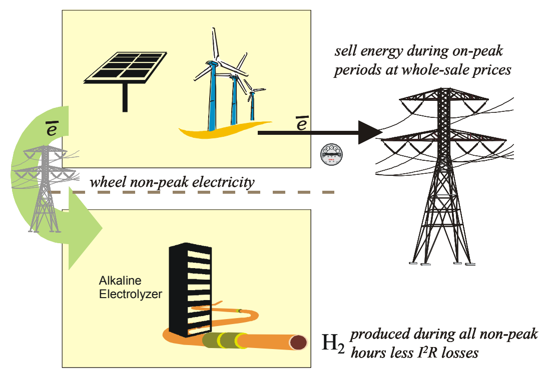



**Figure 19. Scenario 3A: Hydrogen Production Decoupled from Renewables**

Scenario 2B produces the lowest-cost hydrogen. The purchase of non-peak electricity reduces the cost of the hydrogen despite the fact that the electrolyzer is not being operated full-time. It should be noted that scenario 3A is also an economic option that could make sense depending on the market value of the hydrogen and renewable electricity. Additionally, transmitting the energy, as hydrogen or by wire, will affect the delivered cost of the hydrogen. The study also showed that the decrease in cost as we interact with the grid is more drastic for the PV systems than for the wind systems. The reason for this is that the PV systems are operating during the day when higher priced electricity can be sold to the grid. In these cases, the electricity during on-peak periods is worth more than the hydrogen that could have been produced. **The study demonstrated that the value of PV and wind electrolysis can be enhanced through interaction with the grid and different strategies to produce hydrogen at optimum times of the day.**

This study illustrates the importance of looking at the entire system. We still need to consider the access and cost of the transmission and the rates we would have to pay for our electricity or sell our electricity. In a new effort, initially focused on wind, we're looking at several questions related to this systems approach. The first question is, "Which areas of the U.S. are most likely to be used to generate hydrogen and electricity from wind?" From this, we're hoping to determine the optimized cost of a wind system that produces these two products now and in the future. We're also studying opportunities for reducing system cost by designing a hybrid wind electrolyzer system. A combined wind/electrolysis system may provide opportunities for reducing power conversion and storage costs.

Along these lines, we want to identify areas in which R&D could be used to further reduce costs. We're using a combination of several tools to support this analysis effort. Geographical Information Systems, or GIS, is providing spatial data on resource and demand profiles. An NREL-developed model called WinDS, which is a multi-region, multi-time capacity expansion model, is giving us information on the interaction of the wind/electrolysis unit with the grid and how much it will cost us to access and build new transmission. The WinDS model also helps us identify mechanisms for addressing the intermittency of the system. Windstorm, also developed by NREL, is a real-time system control model, and is being used to evaluate the benefits of combined power electronics. By combining the capabilities of GIS, WinDS, and Windstorm, we should be able to better identify the market penetration and research opportunities for wind-produced hydrogen. Model development is expected to be complete by the end of this fiscal year, with results available in 2004. These models will also be adapted to look at hydrogen production from other renewables such as hydro and biomass.

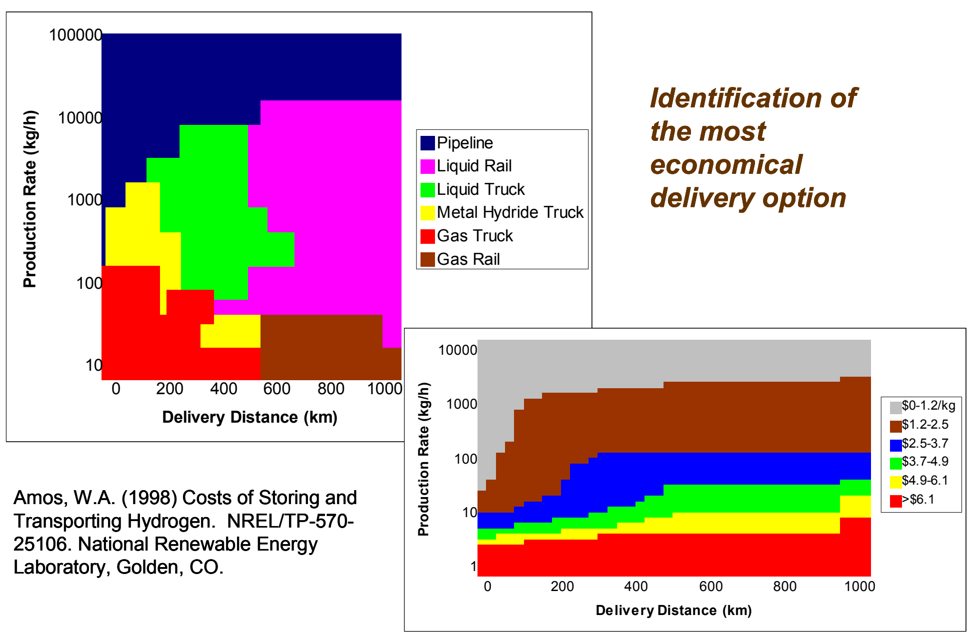



**Figure 20. Hydrogen Storage and Transport Costs**

The next part of any hydrogen system that must be addressed is storage and transportation. The NREL hydrogen delivery model determines the most economical delivery option for different scenarios, as shown in Figure 20. At very high production rates, the most optimal system is a pipeline. So in the long term, we could envision the development of hydrogen pipelines. In the near term, though, with smaller demand rates, gas delivery is more economic. As our delivery distance increases, the more dense forms of delivery through truck into rail become cost-effective. **In terms of the costs of those delivery options, as a function of production rate and delivery distance, what drives the cost is production rate, or demand rate. The delivery distance is far less important than how much you're delivering.**

In summary, determining the feasibility of a hydrogen technology involves a careful look at the entire system (see Figure 21). By only looking at production, resource availability, demand, upstream energy consumption, and delivery costs are overlooked. Co-product opportunities and grid interaction are also important considerations, as significant cost benefits can be realized. **Taking a systems approach provides a much more solid foundation for determining the most cost-effective options for building the hydrogen production, delivery, and end-use infrastructure.**

- More than production
- Resources Important
    - Feedstocks
    - Water
    - Upstream energy
- Co-product opportunities
- Grid interaction
- Delivery is not an adder

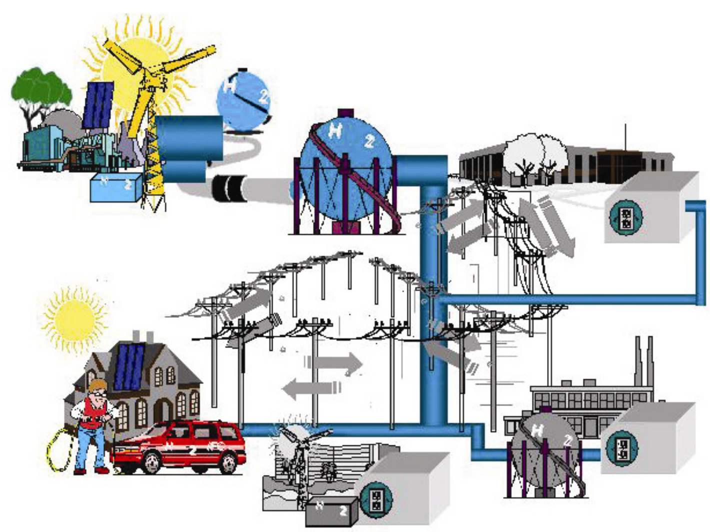


**Figure 21. The System**

***Sivan Kartha***

**The whole transition to hydrogen is a very integrated process that involves plans for production, delivery system, and end use**, which will likely be taking place over the next 40 years or so.

Geographic Information Systems (GIS)-based spatial demand and resource analysis is underway for seven key cities that represent a wide range of different resource bases and spatial characteristics: Atlanta, Boston, Chicago, Denver, Houston, L.A. and Seattle. This project is looking at scenarios current to 2040 for the transition to hydrogen from today's fossil fuel-based system. In the early stages there will be more reliance on onsite production of hydrogen. In later stages expansion into a pipeline infrastructure will be considered.

The penetration rate—the rate at which fuel cell vehicles or stationary fuel cell systems reach the commercial base—will strongly influence interested investors. The quicker the transition happens, the easier it will be to transition to centralized systems with pipelines that can ultimately result in lower delivered hydrogen costs.

The various near term (i.e., available within a decade) supply options include natural gas, although it is not a zero carbon option, and wind and onsite electrolysis. Getting to a zero carbon goal would **depend on a supportive policy context** such as a renewable portfolio standard (RPS), which is already in place in many states, or a carbon cap-and-trade system that is linked to the transport system, not just the electric system. **Then as the hydrogen demand increases, the incremental generation that comes into the electric sector is renewable.** It's really a policy issue as much as it is a technical or new economic issue. We could have a system that is mediated by policies that allow wind in North Dakota to provide power that is delivered to demand centers in Minnesota.

There are actually three ways that an electric sector could respond to that kind of a policy driver for zero-carbon hydrogen from electrolysis. First is more renewables. Second is by shifting from existing coal to new gas, which is less carbon intensive. This would result in an increase in generation without an increase in carbon. Third is zero-carbon options using centralized fossil fuel hydrogen production with carbon sequestration.

Natural gas and coal could be zero carbon feedstocks—if integrated with geological sequestration. **Biomass-to-hydrogen would be zero carbon or even negative carbon, with sequestration. But there are concerns about the permanence of sequestration. Nuclear, of course, has issues associated with extraction, safety, proliferation and waste disposal.**

Figure 22 shows the delivered cost of hydrogen from several supply options. The cost of the refueling station, distribution, transmission, carbon sequestration, fuel, and capital all contribute to the delivered cost of energy. Three electrolysis options are shown, assuming different prices of electricity: 1¢ per kilowatt, 4¢ per kilowatt and 8¢ per kilowatt. Specific options include onsite reforming of natural gas and centralized production of hydrogen from natural gas, biomass, and coal, including the costs of delivery.

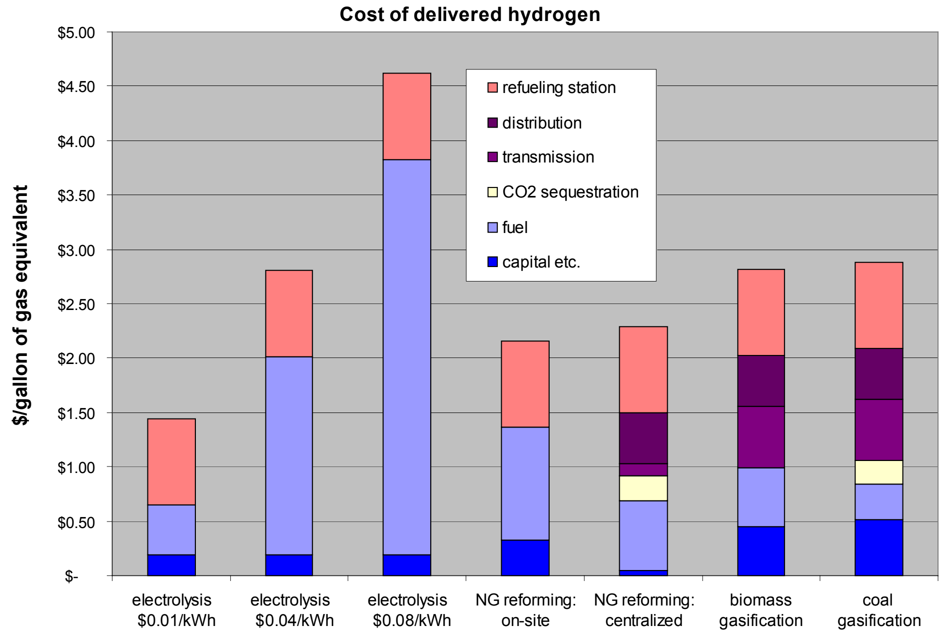



**Figure 22. Hydrogen Supply Options: Delivered Costs**

**There are five factors that seem to be important in deciding whether to options to use renewable electricity for hydrogen in a dedicated configuration or to use renewables electricity in a grid connected configuration.**

**Delivery.** Is the cost of pipelines going to be more or less than the cost of wires? Pipelines are for very high volumes in fairly short distance. Where are your sources of renewable energy compared to your demand centers for hydrogen? Is it long distance or is it short distance?

**Capacity factor.** If you have a dedicated electrolyzer linked to a renewable source, the electrolyzer is only going to be able to be used at the capacity factor of your renewable source. This will triple or quadruple the capital cost of an electrolyzer.

**Storage.** Depending on your system you may already need storage onsite. Or you may need to have storage at a dedicated offsite centralized facility. The amount of storage and whether you would need that storage anyway, with or without intermittent sources, will affect the relative preference of these two options.

**Policy environment.** Grid connected power for zero-carbon hydrogen really only makes sense if the right policy framework is in place—an RPS or some kind of a carbon cap-and-trading regime. If climate is a driving concern then you might want to think about the value of flushing coal out of the electric system before worrying about displacing gasoline with renewable electricity.

**Speed of transition.** The need to put fuel cell vehicles out on the road and develop the infrastructure is another factor. Even if there are long-term concerns about climate, you might want to start working on displacing gasoline even before all the coal is out of the system.

Comparing two scenarios: (1) a hydrogen transition in an otherwise business-as-usual world ("BAU Scenario") and (2) a hydrogen transition in a world where simultaneous efforts are made to reduce greenhouse gas emissions through efficiency and renewables (the "Low-GHG Scenario"), leads to the following conclusions.

First, there is a marked difference between the two scenarios in both the total generation and the generation mix in the electric sector. The Low-GHG Scenario, with concurrent improvements in energy efficiency and implementation of hydrogen-motivating policies, leads to much less electricity demand in the system. In this case, about 10% of the generation ends up being for the purpose of producing hydrogen for fuel cell vehicles. It's the same total amount; same absolute amount in the BAU Scenario - but it's a small fraction of the total.

Next there is the amount of major infrastructural investment to create the electric sector as it expands over the next 40 years. This is much higher in the BAU Scenario than in the Low-GHG Scenario. Both scenarios meet a lot of vehicles' demand for hydrogen, but the amount of growth in electric sector means that a lot of money is being put into electric sector expansion. **Now that's money that is in competition for those infrastructural needs that are needed for putting in place the hydrogen infrastructure.**

Another important implication is the impact on the natural gas sector. How much gas is needed in the BAU Scenario versus the Low-GHG Scenario? In the BAU Scenario, a lot more gas is needed and therefore the price is also higher. This has implications regarding the investment in infrastructure. It also has implications for the cost of delivered hydrogen from natural gas.

**The question is still very much up in the air about how hydrogen will be produced if this transition to hydrogen takes place.** Much depends on the precise scale and the rate of that transition, and how the "technoeconomics" play out across the different options. Just as important is the policy context under which this transition occurs.

### *Economics Panel Discussion and Questions*

Panel Moderator: Harry Braun

**Harry Braun: It takes 18 gallons of water to make a gallon of gasoline from crude oil in the refinery.**

**Ron Larson:** Over the years we've lost a number of technologies. Are there any things that we've lost that we would want to bring back? Any technologies we're missing?

**Henry Kelly:** Ocean wave action has a lot of potential. Also, it's much, much cheaper to save a gallon than it is to produce a gallon. It's just insane not to have a program that recognizes that. There's a long laundry list of things in that category like biotechnologies that can help find a way of teasing bugs into producing hydrogen more efficiently and also do chemistry on organic materials that can produce hydrogen as well as other byproducts. **Getting to be at least as smart as a mustard plant should be a five-year goal. You should be able to get 40% conversion of sunlight into hydrogen. The chemistry of that would be really high on my list.**

**I certainly would revive Ocean Thermal Energy Conversion systems - because they not only could produce an enormous amount of hydrogen and electricity but they also have the unique attribute of producing immense amounts of desalinated ocean water at much lower than conventional costs - because it can be done as a by-product.** They can dramatically enhance fish food yields in the oceans. With that, we can really undo a lot of the damage that we are doing with overfishing - by deploying fleets of ships that are no more difficult to build than an oil tanker.

**Harry Braun: The 250 years supply of coal that we have now would be consumed in about 30 years if you had to depend on it to run the transportation and energy sector.**

**Kert Davies:** In one century, we'll be emitting from underground as much carbon as we're emitting from our smoke stacks and tail pipes. So we could be setting ourselves up for a serious carbon liability if we think we can just all pack carbon away underground without a lot of serious research and monitoring before the fact.

I think the influence of the coal industry and the fact that we have this massively inertial energy system in place that is fossil-based is the main reason why there's such a policy interest. It's interesting to muse about why there's so much more a focus on renewables and so much less focus on sequestration in the European program.

**Maury Albertson:** One of the things that has concerned me is that there's no mention whatsoever of using the carbon to make carbon fiber. Carbon fiber is twelve times as strong as steel, much lighter and we're now making tennis rackets and fishing poles and so on out of that and even a lot of car bodies. It's the structural material of the future. Why don't we include this in the equation? Instead of sequestration?

**Margaret Mann:** From any source that takes the carbon naturally to CO2, you have to convert that $CO_2$ to carbon. It takes a lot of energy. I'm not sure the energy balance is positive.

**Henry Kelly:** It's so cheap to get carbon from other sources that to try to extract a carbon from $CO_2$ is just much more expensive than taking it from even a tree. One thing I should do is give an advertisement for Joan Ogden's most recent energy review paper where she actually does try to go through in detail, costing out all the externality effects of, including security and local air pollution and global climate change. She goes through the thankless task of actually trying to add all this stuff up for a bunch of different options.

## HEALTH AND ENVIRONMENTAL CONSEQUENCES OF NON-RENEWABLE HYDROGEN

This session discussed the environmental consequences that can be avoided using renewables.

- Introduction to Issues & Moderator: Roy McAlister, President, American Hydrogen Association
- Health Impacts: Anthony DeLucia, Chair, Board of Directors, American Lung Association

### *Introduction to Issues & Moderator – Roy McAlister*

I like to ask my students the following question, "What would you do with 100 gallons of oil to realize its highest value?" You would not use it as a fuel. 100 gallons of oil can be made into $3,500 worth of CDs, TVs, corrective lenses, medical components, computers, carpeting, clothing, transportation components, and thousands of other things that are far more valuable than burning it as gasoline or diesel fuel. These high-value products can be produced by converting oil or other renewable hydrocarbons into carbon fibers that are stronger than steel and lighter than aluminum. Hydrogen that is co-produced can be used as the clean fuel of preference. Burning a gallon of gasoline or diesel fuel causes an opportunity cost of about $34 per gallon because the fossil hydrocarbons could have been made into $35 worth of electronic parts, medical devices, or transportation components instead of being burned as a fuel.[50]

In the case of nuclear fuels, we have looked pretty earnestly at how nuclear fuels and wastes might be stored and have realized that **radioactive materials that can be accessed by terrorists can be bad for all of us. The opportunity cost of using fossil energy to mine, refine, and manufacture radioactive fuels for nuclear power plants is enormous. These same fossil reserves could have been made into carbon reinforced wind turbines, wave machines, solar trackers, and many other renewable energy conversion devices. We subsidize every segment of the nuclear industry but get less economical production of electricity and a continuing cost penalty over the next 1,000 centuries[51] for providing expensive security against terrorists or natural events such as earthquakes that might cause releases of these radioactive poisons. If equivalent subsidies had been provided to renewable energy developments in solar, wind, wave, hydro, and biomass technologies, we would have provided sustainable energy supplies that are cleaner and far less dangerous than the nuclear technologies.**[50]

Look at people shopping or making decisions and you find that they're always investing in or buying a better environment. For example, people want to retire to places that have a good environment.  They want to vacation in places that have a good environment. They buy clothes to make a better environment for our body. **We need to be much more aware that the ultimate value that we strive for is nearly always an environmental improvement.**

We need to look internally and worry a little bit about how we're treating our bodies.  For example, fine particles are now correlated with harmful diseases. **The materials that source the fine particles could have been used in better ways.  These pollutants really represent another lost opportunity cost.**  This is part of the opportunity cost that we incur as we decide to burn things that cause harm to our environment and that we could use otherwise to make durable goods.

In terms of management of resources, the methane and carbon dioxide "greenhouse gas" problem could be considered a scandal. We haven't been very responsible in our agricultural and forest programs. We could be sequestering carbon from renewable biomass that now rots or burns to release vast amounts of methane and/or carbon dioxide.

We should be asking the questions, "How can we rearrange our economy and get more durable goods and a better environment?" and  "How can we manage our economy to get better results?"  If this is the defined task we will surely come up with better ways to produce carbon enhanced durable goods and co-produce hydrogen for our energy needs.

One of the really difficult aspects of this comes with **the issue of who should pay? Who should be responsible for respiratory problems, treatment of diseases and lost productivity?**  Who should be the leader in the world regarding what are we going to do about greenhouse gas accumulation and inflationary depletion of strategic supplies of fossil fuels?  What about the casualties and loss of property that occurs as we increase the severity and frequency of weather related damages?  We need to provide answers to these questions by investing in the development of a sustainable economy for a better future.

The world market for hydrogen includes more than 1 billion people that do not have clean drinking water.[52] We need to provide clean energy to produce and distribute drinking water.  2.8 billion persons do not have basic sanitation. *About 25,000 persons die each day from water-borne diseases.*[50,52,53] We need to take human and animal wastes to a new outcome. Renewable methane and/or hydrogen can be produced from sewage and garbage. We can convert the methane into carbon that is ten times stronger than steel, lighter than aluminum, and a better heat conductor than copper. This is a better use of such carbon than having lung disease or adverse greenhouse gas consequences. **We have to seriously ask what is the value of life and what is the good will value for bringing renewable hydrogen solutions to places where there are many deaths per day that can be attributed to the lack of sanitation and/or air pollution due to fossil fuels.**

People need jobs. Large expenditures have been made of earth's resources to build engines, particularly 800 million internal combustion engines. With hydrogen we can make these engines last longer. We can make them actually produce more power and they can perform an actual air cleaning service. **More jobs will be developed to make and distribute renewable hydrogen from solar, wind, wave, hydro, and biomass resources than the fossil fuel industry provides.** These jobs will help define a new economy that is based on anti-inflationary production of renewable energy and materials instead of inflation due to depletion of finite resources.

We need to develop better definitions of values and start looking at opportunity cost seriously as a way for us to do what's important in life. This will help influence the world in a positive way, particularly during this time of transition. We should come away from this Forum with **a resolution to urgently develop what it takes to have a sustainable economy that produces a better environment.** Not only would the U.S. benefit from producing many more wind turbines for our own use but other countries would benefit too. That would be a more prudent export than military arms or fossil fuel dependent electricity generation equipment.

### ***Health Impacts – Anthony DeLucia***

Working toward a renewable hydrogen future will make the world a safer and healthier place to live. If we all do our part, it will thus continue on in that way and be healthy and whole for generations to come.

The historical record regarding pollution associated with fossil fuels shows that, between 1909 and 1953, there were global episodes when the weather changed, resulting in thousands of fatalities. For example, the United States had its first real episode in 1948 in Donora, Pennsylvania.

Ozone, or smog, burns the lungs making it difficult to breath. The tinier components of soot, **fine particulates with aerodynamic diameters less than 2.5 microns (1/30 the diameter of a human hair), are basically the worst problem that we have.** Together these pollutants and other regulated air pollutants are associated with deaths, hospitalizations, emergency room visits, asthma attacks, impaired breathing, decreased lung function, etc. **Studies by the National Academy of Sciences have estimated that annual mean health benefits from the air quality improvement projects in the 1990 amendments to the Clean Air Act save in excess of one hundred billion dollars per year (1990 dollars)**[54].

Recently, in the state of Tennessee and the entire Southeastern U.S. region, questions have been raised as to why the fine particle attributable death rate (primarily due to heart attacks) is four times greater than in a metropolis like New York City? Primarily this inflated death rate results from the continuing use of some of the oldest and thereby dirtiest coal fired power plants in the country[55] (see Figure 23).

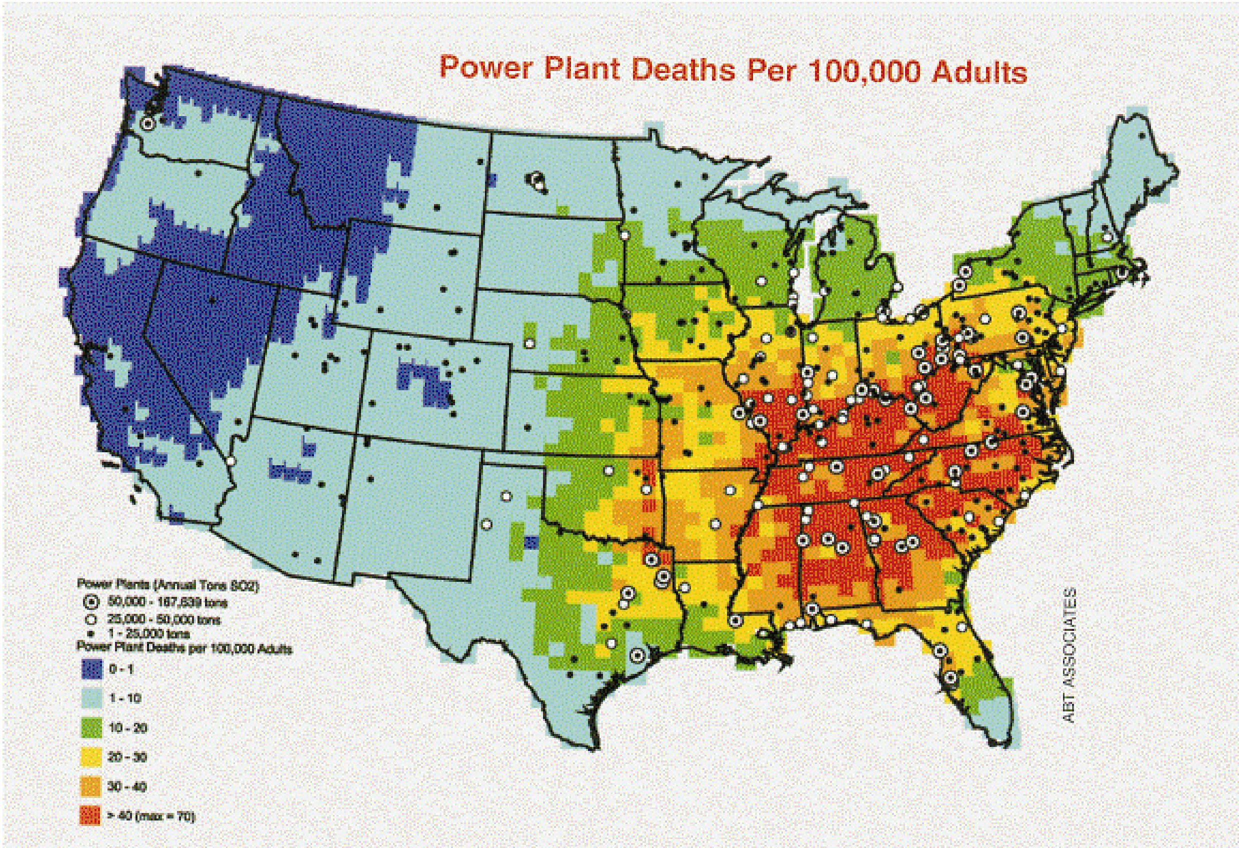
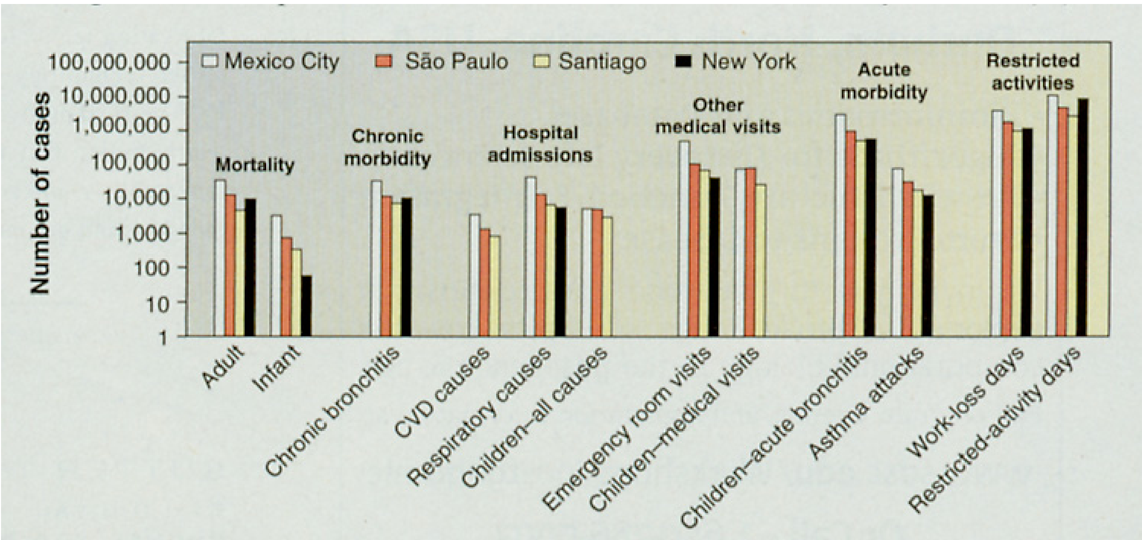


**Figure 23. Nationwide Correlation of Power Plant Emissions and Related Annual Mortality**[55]

In addition to producing fine particles that harm health, the combustion of coal is also harming visibility and ecological health. It also is contributing to a whole host of events and alterations related to climate change, such as the life cycle of infectious disease, bloom of various toxic marine organisms, volatility of storms, drought, etc.

A study published in the journal Environmental Health Perspectives showed that **an estimated 64,000 premature deaths would be saved from the years 2000-2020 in just four cities (New York, Mexico City, Santiago, and Sao Paolo) by implementing GHG policies that concomitantly diminish toxic emissions such as ozone precursors and fine particulates**[56] (see Figure 24).




**Potential human health benefits from reductions in ozone and particulate matter air pollution** associated with implementing GHG mitigation measures (2001–2020) (*18*). CVD, cardiovascular disease.

**Figure 24. Health Effects Avoided from 2000 to 2020 in the Four Cities Analyzed if GHG Mitigation Measures are Taken**[56]

What about the changes in weather-related mortality? During the summer, the combination of heat and pollution is a terrible killer, especially for elderly people. Sprawl leads to longer drives and loss of social capital. **The list goes on and on. The basic question is what kind of world do we want for our children?**

## FORUM SUMMARY

***The following summarizes the main points from the Forum. For more details, please refer back to the Presentation Highlights. References to individual speakers are noted for each point presented.***

***Hydrogen produced from renewable energy sources is sustainable, healthy and secure compared to other fuels that are unsustainable, polluting, and/or a threat to national security.***

**Sustainability.** Hydrogen is not an energy source. Hydrogen is an energy transport and storage medium – a medium that requires more energy to produce than is derived from it in its end use. Hydrogen production can only be sustainable if produced by renewable sources of energy. (Nicklas, Goswami, Brown)

**Health.** Renewable hydrogen will reduce carbon dioxide emissions substantially, decreasing the threat of global warming. (Goswami, Kelly) Using renewable non-polluting fuels to produce hydrogen will protect the health of all Americans. (DeLucia, Friedman, McAlister)

**Security.** Gaining independence from foreign oil is important for energy security. (Garman) Renewable hydrogen can replace petroleum. (Mann) It also reduces long term security risks associated with nuclear power. (McAlister)

***The renewable energy resources in the U.S. are comprehensive and diverse.***

Renewable energy resource analyses show that there are renewable energy resources everywhere in the U.S. and many areas have multiple renewable resources available. The entire country's energy needs can be met with renewable energy. Much can be produced locally. This diversity also is important for national energy security. (Hock, Bull)

***Renewable hydrogen is technically viable today and will become increasingly economically competitive from a diverse array of renewable energy technologies and distribution options.***

Hydrogen can already be produced by a number of technologies that use renewable energy, with some of them already the least cost option in some parts of the country. While many improvements are possible, technology is not a major barrier to renewable hydrogen even in the near term. (Goswami, Kazmerski, Scott) Any car on the road today can be modified to use hydrogen fuel and, with liquid hydrogen, performance and range are not compromised. (Braun)

Over time the costs of all renewable resources will dramatically decrease. (Mann) Wind-produced hydrogen is the most promising since the cost of wind currently is lower than the other renewable resources. (Brown, Hock, Kelly)

The value of solar electric and wind electrolysis can be further enhanced through interaction with the grid and different strategies to produce hydrogen at optimum times of the day. (Mann) The marriage between hydrogen and solar brings secure, clean energy—as well as making PV a *"24-hour power"* option. (Kazmerski)

Concentrating solar power is well positioned for greater use since it is a proven technology, has abundant resources, firm capacity, reliability and dispatchability, and high cost reduction potential (Cohen)

Biomass is already the world's fourth foremost fuel, it is a dispatchable resource, has a reasonable amount of capacity worldwide, and already has created a diverse biomass-based energy economy (Day, Overend) Biomass technology based on gasification or pyrolysis is promising. (Overend)

The thermochemical path has the potential to achieve very high solar energy-to-chemical energy conversion efficiencies. In addition, solar upgrade and decarbonazation of fossil fuels processes provide the link for a smooth transition between today's fossil fuels and tomorrow's solar thermal technology (Steinfeld) Algae is a very promising alternative. There are some significant engineering challenges there, but the productivity potential is increasing. (Overend) Third generation PV and other innovative techniques also are promising. (Bull) Direct splitting of water to produce hydrogen is another exciting, promising direction that should be pursued. (Garman, Bull)

Costs of many renewable approaches have come down over the past two decades and some of the new developments, like nano rectenna conversion and biological photovoltaics, could reduce future costs by orders of magnitude. In the future, renewable energies are the ones that will be cost effective. This conclusion is reached without giving any environmental credit to renewables. (Goswami)

Hybrids of solar electricity with other renewables (e.g., wind and bioenergy) extend this availability to all the United States. Because various solar technologies have potential for building integration, land area requirements are greatly reduced. (Kazmerski)

***Renewable hydrogen limitations due to resources and other factors are not a major concern.***

Renewable energy does not suffer from the same resource limitations as non-renewable energy sources. For example, if coal were used to provide hydrogen for fueling half of the of the light-duty vehicle fleet, coal consumption would increase by 30% in the U.S. and the resource would be depleted much faster than currently projected. (Hock, Nicklas)

Water depletion is not an immediate concern for renewable hydrogen. In transitioning to hydrogen, the use of water to produce it is similar to the amount of water that's currently used in today's energy systems. (Mann) Conservation and/or desalinization could help make the necessary water more available. (Scott)

Dispatchability and intermittency challenges associated with renewable energy as well as transmission line saturation can be addressed by moving hydrogen in pipelines from renewable source to place where the hydrogen is needed. (Braun, Leighty) Dispatchability also is addressed by employing decentralized approaches, the viability of which is currently being demonstrated in projects that use onsite renewable resources, to produce hydrogen onsite, for use onsite. (Shimko) Renewable hydrogen will be particularly economical in places like Hawaii where non-renewable energy is being imported. (Hurwitch)

***Renewable hydrogen becomes even more valuable when the external costs associated with non-renewable fuels and the economic benefits of renewable energy are considered.***

External factors associated with fossil fuels are costly. For example, eliminating chronic diseases such as asthma related to air pollution associated with fossil fuel combustion would save Americans $12 billion/year in health costs. (DeLucia) Roughly $100 billion is spent on importing oil. (Scott) Military costs associated with foreign oil are now becoming obvious to us all. (Braun) Imported liquefied natural gas also poses potential terrorists security problems as well as worsening our energy-related balance of payments deficit. (Nicklas)

Developing a distributed approach to renewable hydrogen in the U.S. will create jobs locally, throughout the country, (Brown, Braun, Goswami) More jobs will be developed to make and distribute renewable hydrogen from solar, wind, wave, hydro, and biomass resources than is currently provided by the fossil fuel industry. These jobs will help define a new economy that is based on anti-inflationary production of renewable energy and materials instead of inflation due to depletion of finite resources. (McAlister)

***Co-benefits make renewable hydrogen even more attractive and cost-competitive.***

Biomass gives an opportunity to sequester carbon by storing carbon in plants. Biomass also can produce a wide range of co-products for the chemicals and fuels markets. (Day) It is better to put carbon into products where it is not harmful, than fuel. (McAlister, Kartha) Desalination of ocean water is another possible by-product of renewable hydrogen. (Kelly) Electricity also can be considered a co-product for wind or solar electric electrolysis. (Mann) The oxygen byproduct of electrolysis is valuable to nearby gasification plants, enhancing the value of hydrogen production from renewable sources like wind. (Leighty)

## MOVING FORWARD: THE RECOMMENDED STEPS

**Create a Shared Vision.** Vision is needed in order to move toward a renewable hydrogen future. This vision needs to be a shared vision by decision makers in government, businesses, and communities. (Friedman)

**Develop a Renewable Hydrogen Literate Population.** To make the vision of a renewable hydrogen future happen, our education system needs to foster citizens that can actually make the vision of a renewable hydrogen future a reality. (Devlin, McAlister) The public needs to be a renewable hydrogen literate population. (Freeman, Brown)

**Understand and Build Public Support.** Public opinion overwhelmingly favors renewable energy over all other energy supply options. However, despite this public support, national energy policy often does not reflect the views of the average American. (Nicklas) A national debate on energy policy is needed to help reinforce these positions among our leaders. (Hurwitch)

**Identify and Quantify Externalities and Risks.** Congress needs to ask GAO to do a study to identify what gasoline really costs and how external costs, not included in the current energy prices, really impact consumers. (Leighty) These external costs must be included in the cost of energy. (Braun) Economic comparative analysis also should include explicit consideration of external risks, such as terrorism. There are also major unknowns and therefore risks with the proposed CO2 sequestration and waste disposal options now, integral to fossil and nuclear strategies. The renewable energy approaches are essentially risk-free. (McAlister)

**Develop Partnerships.** To speed progress toward a renewable hydrogen economy, partnerships between governmental agencies, universities, auto companies and energy companies are needed. (Shimko) A strong industrial base for renewable energy technologies already exists. Renewable hydrogen can be implemented more rapidly than for any other approach, but a speedy introduction can be ensured by working with existing renewable industries. (Nicklas)

**Adopt a Systems Analysis Approach to Planning.** A systems analysis approach provides a solid foundation for determining the most cost-effective options for building the renewable hydrogen production, delivery, and end-use infrastructure. Consideration of the fully integrated system also helps in determining and prioritizing renewable hydrogen research needs. (Bull, Mann, Kartha)

**Integrate Domestic and International Programs.** To most effectively address the exploding worldwide demand for transportation fuels, the U.S. needs to integrate its domestic and its international programs dealing with environmental issues, renewable hydrogen and transportation. (Kelly) The rapidly growing demand for vehicles around the world needs to be recognized and addressed in an environmentally sound manner. (Kelly) Because many other countries having already announced their intent to generate hydrogen only from renewable sources. (Steinfeld) international cooperation could help reduce our country's cost of renewable hydrogen research and development. (Nicklas)

**Secure Adequate Research Funding.** Aggressive, well-funded research in renewable hydrogen is needed to reduce costs of currently viable options and develop additional technological opportunities which could produce even greater long-term benefit. Such investments will help ensure that environmentally sound options will be the most cost effective, long-term solution. (Goswami) The current investment in the full portfolio of technologies needs to be much higher in order to get the necessary work done. (Kelly) With a strong level of investment, renewable hydrogen wIll become a reality within a generation. (Kazmerski) Research programs need to be focusing more on development of renewable energy that will be used to produce the hydrogen, not on fossil and nuclear options that will only perpetuate our environmental and security problems. (McAlister)

**Develop Subsidies and Incentives.** Subsidies also need to be restructured. The World Bank estimates that the annual subsidy to fossil fuels is $210 billion. This financial support needs to be shifted to more environmentally-friendly renewable energy. (Brown, McAlister). Tax incentives and other economic incentives need to be developed for production of hydrogen and renewable technologies. (Kelly, Kartha) Past Federal support for other energy sources dwarfs that provided to renewable energy. (Scott, Nicklas)

**Focus on Benefits of Renewable Hydrogen.** In promoting and taking these next steps as a community and a country, we must all stay focused on the many environmental, health, and security related benefits of a ***renewable hydrogen*** economy and the adverse consequences of a fossil fuel-based energy future. (Goswami, Brown) The decisions we make now will determine whether ultimately we will be fueled by clean, secure and lasting renewable options or non-sustainable approaches. (Nicklas)

# REFERENCE INFORMATION

The reference information compiled from this Forum include:

- Acronyms
- Biographical and Contact Information
- Appendix A: Forum Press Conference Remarks
- Appendix B: Numerical Data from Presenters
- Footnotes

## ACRONYMS

| | |
|---|---|
| ASES | American Solar Energy Society |
| BAU | Business-as-Usual |
| Btu | British thermal unit |
| CSP | Concentrating Solar Power |
| GHG | Greenhouse Gas |
| GIS | Geographical Information Systems |
| ICE | Internal Combustion Engine |
| IPCC | Intergovernmental Panel on Climate Change |
| O&M | Operations and Maintenance |
| PEC | Photoelectrochemical |
| PV | Photovoltaic |
| SMR | Steam Methane Reformation |
| TDM | Thermal Destruction of Methane |

## BIOGRAPHICAL & CONTACT INFORMATION

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International, and a Director of the American Solar Energy Society (ASES). Dr. Goswami is the recipient of over 50 awards and certificates from major scientific and engineering professional societies, including the Charles Greely Abbott Award from ASES, and the John Yellott Award from ASME International. He is a fellow of ASME and ASES. Contact E-mail: Goswami@ufl.edu

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**Jeff Serfass** is the founding President of the National Hydrogen Association (NHA), an 86 member industry-led organization formed in 1990 to promote the development and commercialization of hydrogen-related technologies in aerospace, ground transportation, electric power generation, and other energy applications. Mr. Serfass is President of Technology Transition Corporation, a company that manages the NHA, the Solar Electric Power Association, and United States Advanced Ceramics Association, and provides technical, market and staff support to the Partnership for Advancing the Transition to Hydrogen and other private clients in hydrogen, fuel cells, solar and electric utility businesses. His pervious experience includes work as Director of Utility Rates and Energy Management at the U.S. Department of Energy's Energy Regulatory Administration; Program Manager for Electric Energy System Division, U.S. Energy Research and Development Administration; and Corporate Marketing and Power Systems Planning at Westinghouse Electric Corporation. E-mail: jserfass@ttcorp.com

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He is presently leading the Solar Chemistry Annex of the International Energy Agency's SolarPACES Program and serving as the Chair of the Solar Chemistry Committee of the ASME Solar Energy Division. He further serves as Associate Editor of *Energy-The International Journal* and *ASME-Journal of Solar Energy Engineering*. Dr. Steinfeld is founding board member of the *Swiss Hydrogen Association*. E-mail: aldo.steinfeld@eth.ch; Web: www.pre.ethz.ch

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## APPENDIX A: Forum Press Conference Remarks

***The following are the Forum press conference highlights.***

***Mike Nicklas – Chair, American Solar Energy Society***

For those that are new to the American Solar Energy Society, ASES was formed in 1954 to promote the utilization of solar energy. It is the US section of the International Solar Energy Society—a society that has about 30,000 + members in 108 countries. Our society promotes renewable energy—solar energy in the broad sense—including wind, biomass and all the other renewable technologies. Although the benefits of a hydrogen economy are still years away, our biggest challenges, from a sustainability standpoint, are here today. The decisions we make, today, as a country, the research that we choose to support, and the demonstration projects that we fund now will no doubt determine whether our hydrogen future will ultimately be fueled by environmentally-sound renewable energy or non-sustainable approaches. ASES' goal is to bring focus to the issues surrounding the debate over the hydrogen future. **Our goal is to inform all Americans that it is the production source and not the hydrogen itself that will ultimately determine the environmental ramifications, health impacts, and security fears that we will face in the decades ahead.**

Using today's large, centralized hydrogen reforming technologies, we can derive only one-third of the energy input. Although smaller, localized hydrogen production facilities using electrolysis eliminate the penalties associated with liquefying, piping and delivering, one quarter of the energy input is still lost. Making hydrogen from non-renewable energy is not sustainable. Even though hydrogen itself is clean, any process that utilizes fossil fuels or nuclear power to produce it will result in further environmental damage and depletion of finite resources. Even though our country has 250 years of coal supply left, if we were to take that resource and divert it to hydrogen production, coal use would have to increase by 60 percent and coal would be depleted in a fraction of this time, with significant global warming consequences. The nuclear industry also sees itself as a solution to global warming. However, to be a solution, the hundreds of new nuclear plants that will be required to meet the hydrogen demands will need to be secure, have reliable sources of fuel, and address the waste issues. Given these concerns and our fears over homeland security, nuclear seems very unlikely. Up to several months ago, many people thought natural gas might be the solution. However, recent price increases are an indication of the limited amount of natural gas.

We hope to focus the nation on these critical issues at this important time. We are at a point in history where we are beginning to see a paradigm shift in terms of our energy. We need to make our leaders aware of what's happening right now. Some believe that we should gamble the hundreds of billions of dollars on carbon sequestration as a strategy to get us to a hydrogen economy. Others feel that the nuclear industry's problems associated with security, waste, and reliability will be overcome. ASES doesn't think so. When we think of a future energy paradigm based upon hydrogen, we should keep in mind that **hydrogen is not the energy source. Hydrogen is an**

**energy transport and storage medium – a medium that requires more energy to produce than is derived from it in its end use. If this transformation process is not accomplished with renewable energy, we do not have a sustainable energy future.**

***Lester Brown – President, Earth Policy Institute***

We're seeing extraordinary growth and dependence on wind in some areas. There are many reasons why wind has been growing so fast. It's abundant, cheap, inexhaustible, it's clean, climate benign, and widely distributed. No other energy source currently has these attributes. This makes for a powerful combination and one that is going to favor growing public interest in wind resources. Three of the wind-rich states—North Dakota, Kansas, and Texas—have enough harnessable wind energy to satisfy national electricity needs. Worldwide availability is also increasing. China can easily double its current electricity generation from wind alone. In Western Europe there's enough harnessable offshore wind energy to satisfy Europe's electricity needs.

***Yogi Goswami – Vice President, International Solar Energy Society; Senior Vice President, American Society of Mechanical Engineers***

For this planet, in terms of energy, really there is only one income. That is what comes in from the sun. Nature transforms solar energy into different forms for us to use like wind, biomass, the ocean and so on. Nature has tried to save part of that energy for us for a day when we really need it. It took nature millions of years to save the part we have in the ground as fossil fuels and it took us hundreds years to deplete most of it. That is not a sustainable path. Furthermore, use of these fossil fuels has caused environmental problems that are causing us to think seriously about energy sources. Are we improving our quality of life or are we bringing it down with our energy choices? Clean hydrogen can only come from clean energy sources. **Renewable hydrogen will help us improve the quality of our lives and that of the planet.**

## APPENDIX B: Numerical Data from Presenters

***Ron Larson, Chair Renewable Hydrogen Forum; Board of Directors, American Solar Energy Society***

This Appendix provides a summary of much of the considerable amount of quantitative information presented at the Forum. The information was taken from the presentation highlights and/or was derived from the Power Point presentations available on the ASES Website (http://www.ases.org).

***For more detailed information on the analyses represented in the following table, please contact the individual presenters.***

The transition to a hydrogen economy will take a long time– and during that time the renewable energy options will continue to show the impressive cost reductions seen in the past several decades. To illustrate these trends, estimates are presented for the 1980 to 2040 period.

The following numerical data underscores the wide range of attractive, promising renewable hydrogen options.

## PART I - CURRENT AND NEAR TERM POTENTIAL FOR RENEWABLE HYDROGEN

| | | | | **Year of Data (usually)** | | | | |
|---|---|---|---|---|---|---|---|---|
| **Presenter/Topic** | **1980** | **1990** | **2000** | **2003** | **2010** | **2020** | **2030** | **2040** |
| **Yogi Goswami** | | | | | | | | |
| Slide 22: H2 from Natural gas ($/GJ) | | | | $10/GJ | 14 | 24 | 45 | >60 |
| from coal gasification | | | | $17/GJ | 18 | 21 | 26 | 33 |
| from grid electrolysis | | | | $24/GJ | 25 | 30 | 39 | 50 |
| PV | | | | $54/GJ | 37 | | | |
| Solar "antenna" | | | | | | $17/GJ | 14 | 12 |
| Solar Thermal | | | | $39/GJ | | | | |
| Ammonia | | | | | 22 | 18 | 16 | 15 |
| **From Kazmerski PPt and paper** | | | | | | | | |
| System Price ($/Watt) | | | | $6-$15 | $3-$4 | $1.50-$2.00 | ~$1.00/W | ~$0.50/W |
| Electricity Price, $/kWh | | | | $.18-.25 | .11 - .16 | 0.06 | ~.04 | ~.03 |
| U.S. Capacity (GW) | | | | 0.2-0.4 | 0.8-1.0 | | | |
| Same (TWh) - Total U.S. electrical demand | | | | | | | | 1500-2000 |
| Targets - Percent of new (added) U.S. generation capacity | | | | | 15% | | | |
| Percent of total U.S. generation capacity | | | | | | | 10% | 20-30% |
| Performance-highest: for cell | | | | 10-20% | 20-25% | 22-28% | 30-40% | |
| for module | | | | 12-17% | 16-18% | 20-22% | 25-30% | |
| for system | | | | 8-12% | 15% | 16-20% | 20-25% | |
| Distributed Hydrogen: Solar Park (Electrolysis) | | | | | | | | |
| Total Price | | | | $4.70/kg | $2.50/kg | | | |
| Electricity Price portion | | | | $1.90/kg | $1.60/kg | | | |
| Distributed Hydrogen: Residence (Electrolysis) | | | | | | | | |
| Total Price | | | | $7.40/kg | $3.80/kg | | | |
| Electricity Price portion | | | | $4.10/kg | $2.80/kg | | | |
| Distributed Hydrogen: Photolysis (Electrochemical) | | | | | | | | |
| Price | | | | N/A | $22/kg | $5/kg (in 2015) | | |
| Efficiency (solar to hydrogen) | | | | 7% | 9% | 14% (in 2015) | | |
| **Paul Scott** | | | | | | | | |
| Slide # 16 - wind and H2 storage | | | | | In 2013: $4/kg at car; 5c/mile | | | |
| **Danny Day - see http://www.eprida.com/hydro/ ;** date uncertain; greater income from Charcoal as co-product | | | | | | | | |
| Large biomass plant - cost of H2 | | | | | | $1/kg thought to be profitable | | |
| **Gilbert Cohen - discussion only of electricity costs** | | | | | | | | |
| Slide # 16; Solar thermal c/kWh | | | 11c/kWh | 9 | 6 | 4 | | |
| **Ralph Overend** | | | | | | | | |
| Slide # 9 - Switchgrass input fuel cost | | | | $.04/kg | | | | |
| Statement during presentation; date uncertain | | | | | H2 @ $1.50/gallon equivalent - pyrolysis | | | |

## PART II - FUTURE OF RENEWABLE HYDROGEN

| Presenter/Topic | 1980 | 1990 | 2000 | 2003 | 2010 | 2020 | 2030 | 2040 |
|---|---|---|---|---|---|---|---|---|
| | | | | Year of Data (usually) | | | | |
| **David Friedman** Emphasis on transportation sector | | | | | | | | |
| Slide # 4 - Projected total energy use in transportation sector: | | | | | | | 37.8 Quads (2025) | |
| Slide # 9 - Ratio of improvement in Climate Change and Air Quality - Renewable H2 vs. gasoline | | | | | | | about 20 times better | |
| Slide # 10 - Quads of RE H2 to reduce GHG by 150 MMTCE (from 670 to 520, today at 350) | | | | | | | 2.2 Quads | |
| Slide # 14 - kg of carbon per H2 gallon of gas-equivalent with H2 from NG-generated electricity | | | | | | | 31.5 kg | |
| same from PV | | | | | | | 1.5 kg | |
| **Bill Leighty -** numerous wind scenarios with both electric and H2 transmission analyses | | | | | | | | |
| Slide # 59- Wind with 1000 km H2 pipeline | | | | | $ 3.68 – 4.34 / gal gasoline equivalent | | | |
| Many similar detailed computations and comparisons; DC transmission better than H2 pipeline | | | | | | | | |
| N+A93eed Natural gas price >$15/MMBtu | | | | | | | | |
| **Martin Shimko** - Hydro power with electrolyzer, resale at peak cost times | | | | | | | | |
| Slide # 17 - Years for payback | | | | 10 Years | 3 Years | | | |
| **John Hurwitch** Numerous RE options for Hawaii - including noting geothermal and OTEC | | | | | | | | |
| Slides # 4 and 5- high conventional costs now in Hawaii | | | 20 c/kWh; $2.00/gallon | | | | | |
| **PART III - FUTURE RESEARCH NEEDS** | | | | | | | | |
| **Sue Hock** - Overview - numerous RE options | | | | | | | | |
| Slide 9 --PV | | | | | 8.2 $/kg | | | |
| Grid at 6c/kWh | | | | | 3.8 $/kg | *(below all in 2015)* | | |
| Biomass - pyrolysis | | | | 3.8 $/kg | 3.0 $/kg | 2.4 $/kg | | |
| Biomass - pyrolysis | | | | 3.6 $/kg | 2.7 $/kg | 2.0 $/kg | | |
| Wind | | | | 3.6 $/kg | 1.6 $/kg | 1.5 $/kg | | |
| Slide 10 - Photobiological | | | | 200 $/kg | 25 $/kg | 2 to 3 $/kg | | |
| Photoelectrochemical | | | | >500 $/kg | 22 $/kg | 2 to 3 $/kg | | |
| Slide 12 - requirements for 40 Million tons of H2/yr (for 100 Million cars) | | | | | | | | |
| Land for wind and PV | | | | *North Dakota potential and White Sands (3750 sqmi)* | | | | |
| Tons of gas, coal and biomass | | | | | | *95, 310, and 400-800 Million tons* | | |
| **Aldo Steinfeld** - Concentrating Solar Power - chemical conversion technology (not economics) | | | | | | | | |
| Slide 13: Predicted optimum conditions for efficiency, concentration ratio, temperature | | | | | | | *75%, 5000, 1507 K* | |
| In text: "[costs] can be competitive …with electrolysis....solar generated electricity" | | | | | | | | |
| **Dale Rogers -** Concentrating Solar Power - emphasis in Spain | | | | | | | | |
| Slide 8 - "55% of the cost of producing chemicals is in purchased energy" | | | | | | | | |
| **Ralph Overend** (presentation on algae) | | | | | | | *date unspecified below:* | |
| Slide 17 Production cost | | | | *100 - 200 $/kg* | | | *10 $/kg "or less"* | |
| **Second Panel:** | | | | | | | | |
| **Stan Bull** - Covering numerous promising RE approaches in Research phases | | | | | | | | |
| Slide 23 - Weight Ratio of CO2 emissions to H2 produced during conventional SMR: approx. 20 | | | | | | | | |
| **KEYNOTE ADDRESS** | | | | | | | | |
| **Lester Brown -** no slides | | | | | | | | |
| Wind annual introduction growth rate: | | | | over last 7 years - 32%annual growth rate | | | | |
| Percent of electricity supply: | | | | Denmark - 18%; Spain 22%; Northern Germany - 28% | | | | |
| Cost drop per doubling of cumulative installed MWs | | | | -15% | | | | |
| Farmer earnings and losses for 1/4 acre site rental: | | | | $2000, $100 | | | | |
| World Bank estimate of annual fossil fuel subsidy | | | | $210 Billion | | | | |

## PART IV - ECONOMICS OF RENEWABLE HYDROGEN

| Presenter/Topic | 1980 | 1990 | 2000 | 2003 | 2010 | 2020 | 2030 | 2040 |
|---|---|---|---|---|---|---|---|---|
| | | | | **Year of Data (usually)** | | | | |
| **Harry Braun** - emphasis on urgency of action | | | | | | | | |
| Slide # 25 Number of 1MW wind generators needed for 100 Quads/year: | | | | | 12 Million | | | |
| Slide # 26 Number of Autos produced in US per year | | | | | 17 Million | | | |
| **Henry Kelly** | | | | | | | | |
| Slide # 2 - World Energy Consumption | | | | ~420 quads | 493 Quads | 612 Quads | | |
| Slide # 3 - Average Power Levels - for world | | | | 2 kW | | | | 1kW - goal? |
| West Europe | | | | 5 kW | | | | 1kW - goal? |
| North America | | | | 11.5 kW | | | | 1 kW - goal? |
| Slide # 8 - Cost of H2 from biomass - approx. 1/2 each for production and delivery | | | | | | $2.50/gallon equivalent - date ? | | |
| Slide #10 - H2 fuel cell net energy reductions | | | | | | 56-59% (projected) | | |
| Slide # 13 - US DoE Hydrogen Program Annual Funding | | | | $360 Million | | | | |
| Slide # 14 - Similar, all-Europe, 4-year average | | | | $500 Million | | | | |
| Slide # 21 - Cost of Fuel Cell | | | | >$325/kW | | $45/kW (goal) | | |
| Slide # 23 - Cost of defense of Middle East | | | | $0.35-$1.05 /gallon | | | | |
| **Margaret Mann** | | | | | | | | |
| Slide # 3: H2 from Natural gas - tube tanks, plant gate | | | | $7.2 - 11.0/kg | | | | |
| Slide #4 - estimated from five graphs - Electricity Prices (c/kWh) | | | | | | | | |
| Wind | 34 c/kWh | 9 | 3 | 2.8 | 2+ | 2- | | |
| PV | 95 | 45 | 27 | 22 | 15 | 10 | | |
| Geothermal | 9.5 | 5 | 3 | 3 | 2.5 | 2 | | |
| Solar Thermal | 60 | 22 | 10 | 8 | 4 | 3 | | |
| Biomass | 12 | 9 | 7.5 | 7 | 6 | 6 | | |
| Slide # 5 - 1 Barrel petroleum same as | | | | 25 kg of H2 | | | | |
| Approximate reduction of CO2 due to 1 kg of renewable H2 | | | | 3 kg of CO2 | | | | |
| Slide # 9, from biomass | | | | | | $1.60 to $2.60/kg - date uncertain | | |
| Slide # 13, from wind | | | | | | $3.0/kg best scenario | | |
| from PV | | | | | | $5.0/kg, best scenario | | |
| Slide # 21, storage and transportation costs | | | | | | $2 - $5/kg main region; date ? | | |
| Slide # 22 - same costs disaggregated, many scenarios | | | | | | $0.2 to $1.70,/kg; | | |
| **Sivan Kartha** | | | | | | (three below not based by year) | | |
| Slide # 5 - Costs vs. penetratic | at indicated percent penetration | | | | $2.00/gal | $1/gal | $.50/gal | |
| | penetration percentage | | | | 5% | 10% | 25% | |
| Slide # 10 - kg C avoided per MWh of renewable H2 | | | | | | | | |
| in form of displaced gasoline | | | | 75 kg | | | | |
| in form of displaced coal-based electricity | | | | 220 kg | | (Below - estimates taken from graph) | | |
| Slide # 13 ; RE supplied - BAU scenario, TWh | | | | 350 | 350 | 350 | 350 | 350 |
| | in % | | | 10% | 8% | 7% | 6% | 5% |
| Same in Greenhouse Gas Reduction scenario in TWh | | | | 350 | 700 | 900 | 800 | 700 |
| | in % | | | 10% | 10% | 30% | 35% | 39% |
| Slide # 16 - Annual carrying charges in 2025 - BAU scenario | | | | | $23 Billion for Gen'n, 26 Billion for Trans'n | | | |
| | same for GHG scenario | | | | $0 Billion | | | |
| Slides # 17 and 18: Show large predicted differences in use and costs for both Natural Gas and Petroleum for two scenarios | | | | | | | | |
| Slide # 23 - Millions of vehicles in 2040 - totaling 350 Million | | | | | | H2 FC | Gas Hybrid | Gas ICE |
| | | | BAU in 2040 | | | 80 million | 30 | 240 |
| | | | GHG in 2040 | | | 75 | 135 | 140 |

**PART V - EXTERNALITIES AND HEALTH**

**Roy McAlister**

| | |
|---|---|
| Slide # 4 - Tons of particulates per year from power plants | 300,000 tons |
| Excess deaths caused by particulates | 15,000 to 30,000 |
| Slide # 5 - Mercury - % of total from coal-fired power plants | 99% |
| Tons mercury per year | 50 tons Hg /year |
| Amount in 25 acre lake to make fish-eating unsafe | .002 pounds Hg / year |
| Slide # 21 - Daily solar input to energy used by civilization | Ratio = 18000 |

**Anthony DeLucia**

Slide # 15 - Shows close correlation between 4000 deaths and high particulate concentrations over 15 days in 1952 London

Slide # 20 - increase in deaths from lung and heart-related illnesses most polluted to least polluted cities:
about 36% more (1993 data)

Slide # 30 - Asthma deaths per 100,000 population, ann 2 (approximately twice this for blacks)

## ENDNOTES


[1] Goswami, D.Y**.**, Mirabel, S.T., Goel, N., and Ingley, H.A., "A Review of Hydrogen Production Technologies" Proceedings of the First International Conference on Fuel Cell Science, Engineering and Technology, Rochester, New York, April 21-23, 2003.

[2]M.G. Thomas, H.N. Post, and R. DeBlasio, Progr. Photovolt. Res. Appl. 7, 1-19 (1999).

[3] Kazmerski personal communication (2003).

[4]L.L. Kazmerski, Proc. 39th IEEE Photovoltaics Spec. Conf., New Orleans (IEEE, New York; 2003) pp. 21-27.

[5]T. Surek and L.L. Kazmerski, SPIE *oeMagazine* (SPIE, Bellingham, WA.) May, 2003, pp. 24-27.

[6]G. Davis, Evolving Sources or Revolutionary Technology—Exploring Alternative Energy Paths to 2050, Proc. Oil & Money Conference, London, October, 2001 (pp. 1-11).

[7]*National Vision of America's Transition to a Hydrogen Economy to 2030 and Beyond,* February, 2002.

[8]*National Hydrogen Energy Roadmap,* November, 2002.

[9]J. Deutch and E. Moniz, Editorial, N-Power Key to World's Future, Arizona Daily Star, Friday, August 15, 2003 (www.azstarnet.com).

[10]*Hydrogen, Fuel Cells & Infrastructure Technologies Program, Multi-Year Research, Development and Demonstration Plan* (U.S. Department of Energy, Energy Efficiency and Renewable Energy, Washington, DC) Draft, June, 2003.

[11]*National Energy Policy, Report of the National Energy Policy Development Group*, May, 2001.

[12]L.L. Kazmerski, Solar Today, Voi. 16, No. 4, pp. 40-43, 2002.

[13]J.A. Turner, Science, Vol. 285, July 30, 1999, pp. 687-689.

[14]See, for example, New York Times, August 15, 2003

[15]Solar Electric Power: U.S. Photovoltaics Industry Roadmap (U.S. PV Industry; May, 2001).

[16]Gagosian, Robert "Abrupt Climate Change: Should We Be Worried?**", World Economic Forum**, *Davos, Switzerland, January 27, 2003* (http://www.whoi.edu/institutes/images/Abruptclimatechange.pdf )

[17]Obersteiner, et al, "Biomass Energy, Carbon Removal and Permanent Sequestration. A 'Real Option' for Managing Climate Risk", (2002), International Institute for Applied Systems Analysis, Interim Report iR-02-042 http://www.iiasa.ac.at/Publications/Documents/IR-02-042.pdf

[18]Frink, Douglas, "The Chemical Variability of Carbonized Organic Matter through Time", Archaeology of Eastern North America 20:67-79 (1992) http://www.eprida.com/hydro/ecoss/background/charstability.pdf

[19]Day, 2003, internal study, http://www.eprida.com/hydro/ecoss/catgrass/

[20]Glaser, et al. *"Potential of Pyrolyzed Organic Matter in Soil Amelioration",* 12TH International soil Conservation Organization Conference (2002), Vol III, p421

[21]Glaser, B. et al., "Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review", Biol Fertil Soils (2002) 35:219–230, http://www.springerlink.com/openurl.asp?genre=journal&eissn=1432-0789

[22]email correspondence between Day and Czernik, S. (National Renewable Energy Laboratory), March 2003.
http://www.eprida.com/hydro/ecoss/background/czernikemail.txt

[23] Chum, H. L. and R. P. Overend (2003). Biomass and Bioenergy in the United States. inAdvances in Solar Energy: an Annual Review. Volume 15. Ed. Yogi Goswami. pp 83 - 148.Boulder, CO. USA., American Solar Energy Society.

[24] Pacific Northwest Laboratory 1991. *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States,* prepared by D.L. Elliott, L.L. Wendell, and G.L. Gower for PNL, PNL-7789 / NTIS no. DE91018887, September.

[25] The Conversion Project and The International Hydrogen Transmission Test Facility (IHTTF): Accelerating the Switch from Gasoline to Wind-source Hydrogen for Vehicle Fuel, W. Leighty and A. Duskin, *Proceedings of Windpower 2003,* Austin, TX, 21 May 03, American Wind Energy Association

[26] Pacific Northwest Laboratory 1991. *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States,* prepared by D.L. Elliott, L.L. Wendell, and G.L. Gower for PNL, PNL-7789 / NTIS no. DE91018887, September.

[27] The Conversion Project and The International Hydrogen Transmission Test Facility (IHTTF): Accelerating the Switch from Gasoline to Wind-source Hydrogen for Vehicle Fuel, W. Leighty and A. Duskin, *Proceedings of Windpower 2003,* Austin, TX, 21 May 03, American Wind Energy Association

[28] *Hydrogen Delivery Technologies and Systems: Pipeline Transmission of Hydrogen*, Air Liquide, Strategic Initiatives for Hydrogen Delivery Workshop May 7-8, 2003 ,U.S. Department of Energy Hydrogen, Fuel Cells, and Infrastructure Technologies Program

[29] Steinfeld A., Palumbo R., "Solar Thermochemical Process Technology", *Encyclopedia of Physical Science and Technology*, R. A. Meyers Ed., Academic Press, Vol. 15, pp. 237-256, 200.

[30] Steinfeld A., "Solar Hydrogen Production via a 2-step Water-Splitting Thermochemical Cycle based on Zn/ZnO Redox Reactions", *International Journal of Hydrogen Energy*, Vol. 27, pp. 611-619, 2002.

[31] V. Zedtwitz P., Steinfeld A., "The Solar Thermal Gasification of Coal — Energy conversion efficiency and $CO_2$ mitigation potential", *Energy - The International Journal*, Vol. 28, No. 5, pp. 441-456, 2003.

[32] Hirsch D., Epstein M., Steinfeld A., "The Solar Thermal Decarbonization of Natural Gas"; *International Journal of Hydrogen Energy*, Vol. 26, pp. 1023-1033, 2001.]

[33] Research at ETH/PSI on Solar Hydrogen: www.pre.ethz.ch

[34] Khaselev, O.;Turner, J. A. "Monolithic Photovoltaic-Photoelectrochemical Device for Hydrogen Production via Water Splitting." Science. Vol. 280 17 April 1998 pp. 425-427

[35] For more information, see Lester R. Brown, *Eco-Economy, Building an Economy for the Earth* (New York: W.W. Norton & Company, 2001) and Lester R. Brown, *Plan B: Rescuing a Planet under Stress and a Civilization in Trouble* (New York: W.W. Norton & Company, 2003). Additional information is available at www.earth-policy.org.

[36] Economic growth from International Monetary Fund, *World Economic Outlook Database* (Washington, DC: various updates).

[37] Oil production from BP, *BP Statistical Review of World Energy* (London: Group Media Publications, various years); paper consumption calculated from U.N. Food and Agriculture Organization, *FAOSTAT Statistics Database*, <apps.fao.org>, updated 7 February 2001. All population estimates from *World Population Prospects: The 2002 Revision* (New York: February 2003).

[38] Ralph Torrie, Richard Parfett, and Paul Steenhof, *Kyoto and Beyond: The Low-Emission Path to Innovation and Efficiency* (Ottawa: The David Suzuki Foundation and Climate Action Network Canada, October 2002); Marty Mittelstaedt, "Putting Out the Fires," (Toronto) *Globe and Mail*, 15 March 2003.

[39] U.S. Department of Agriculture (USDA), *Production, Supply, and Distribution*, electronic database, Washington, DC, updated March 2003.

[40] Global temperature from Goddard Institute for Space Studies, NASA Goddard Space Flight Center Earth Sciences Directorate, "Global Temperature Anomalies in .01 C," at <www.giss.nasa.gov/data/update/gistemp/GLB.Ts.txt>, viewed April 2003.

[41] John E. Sheehy, International Rice Research Institute, Philippines, e-mail to Janet Larsen, Earth Policy Institute, 1 October 2002; Pedro Sanchez, "The Climate Change–Soil Fertility–Food Security Nexus," speech, *Sustainable Food Security for All By 2020*, Bonn, Germany, 4–6 September 2002; David Elstein et al., "Leading the Way in $CO_2$ Research," *Agricultural Research*, October 2002.

[42] David B. Lobell and Gregory P. Asner, "Climate and Management Contributions to Recent Trends in U.S. Agricultural Yields," *Science*, 14 February 2003.

[43] Chinese trade surplus with the United States from U.S. Census Bureau, "U.S. Trade Balance with China," at <www.census.gov/foreign-trade/balance/c5700.html>, updated monthly.

[44] Soren Krohn, "Wind Energy Policy in Denmark: Status 2002," Danish Wind Energy Association, at <www.windpower.org/articles/energypo.htm>, February 2002; American Wind Energy Association, *Global Wind Energy Market Report* (Washington, DC: March 2002), p. 3; Felix Avia Aranda and Ignacio Cruz Cruz, "Breezing Ahead: The Spanish Wind Energy Market," *Renewable Energy World*, May–June 2000.

[45] According to Debra Lew and Jeffrey Logan, "Energizing China's Wind Power Sector," Pacific Northwest Laboratory, March 2001, at <www.pnl.gov/ china/ChinaWnd.htm>, China has at least 275 gigawatts of exploitable wind potential, roughly equal to the current installed electrical capacity in China as reported by U.S. Department of Energy (DOE), Energy Information Administration (EIA), "China," *EIA Country Analysis Briefs*, at <www.eia.doe.gov/emeu/cabs>, updated June 2002; offshore wind energy in Europe from European Wind Energy Association and Greenpeace, *Wind Force 12: A Blueprint to Achieve 12% of the World's Electricity From Wind Power by 2020* (Brussels and Amsterdam: 2002), pp. 25–26. According to the 1991 assessment of wind energy resources in the United States, Texas, North Dakota, and Kansas would be able to produce 3,470 billion kilowatt-hours (kWh), approaching the 3,779 billion kWh used by the United States in 2001, as reported by DOE, EIA, "United States," *EIA Country Analysis Brief*s, updated November 2002. See D. L. Elliott, L. L. Wendell, and G. L. Gower, *An Assessment of the Available Windy Land Area and Wind Energy Potential in the Contiguous United States* (Richland, WA: Pacific Northwest Laboratory, 1991); state maps available from AWEA at <www.awea.org/projects/index.html>, last updated 23 January 2003. Recent wind potential assessments reveal that the capacity is greater than estimated in the 1991 survey, for more information see Cristina L. Archer and Mark Z. Jacobson, "Spatial and Temporal Distributions of U.S. Winds and Wind Power at 80 m Derived From Measurements," *Journal of Geophysical Research*, vol. 108, no. D9, 13 May 2003.

[46] Larry Flowers, NREL, "Wind Power Update," at <www.eren.doe.gov/windpoweringamerica/pdfs/wpa/wpa_update.pdf>, viewed 19 June

2002; Glenn Hasek, “Powering the Future,” *Industry Week*, 1 May 2000; David Milborrow, “Size Matters—Getting Bigger and Cheaper,” *Windpower Monthly*, January 2003, pp. 35–38.

[47] For corn, calculations by Lester Brown from John Dittrich, American Corn Growers Association, “Major Crops: A 27-Year History with Inflation Adjustments,” Key Indicators of the U.S. Farm Sector (Washington, DC: January 2002); wind royalties from Union of Concerned Scientists, “Farming the Wind: Wind Power and Agriculture,” at <www.ucsusa.org/energy/ fact_wind.html>.

[48] World Bank, *World Development Report 1999/2000* (New York: Oxford University Press, 2000), p. 100.

[49] Fossil fuel subsidies from Bjorn Larsen, *World Fossil Fuel Subsidies and Global Carbon Emissions in a Model with Interfuel Substitution*, Policy Research Working Paper 1256 (Washington, DC: World Bank, 1994), p. 7.

[50]McAlister, R. E. “*The Solar Hydrogen Civilization*” ISBN 0-9728375-0-7 (2003) www.americanhydrogen.com,

[51]El-Wakil, M. M., “Nuclear Power Engineering” pages 62-63, McGraw-Hill Book Co. (1962)

[52]Bern C et al. “The magnitude of the global problem of diarrhoeal disease: a ten-year update”, *Bulletin of the World Health Organization* 1992, 70:705-14.

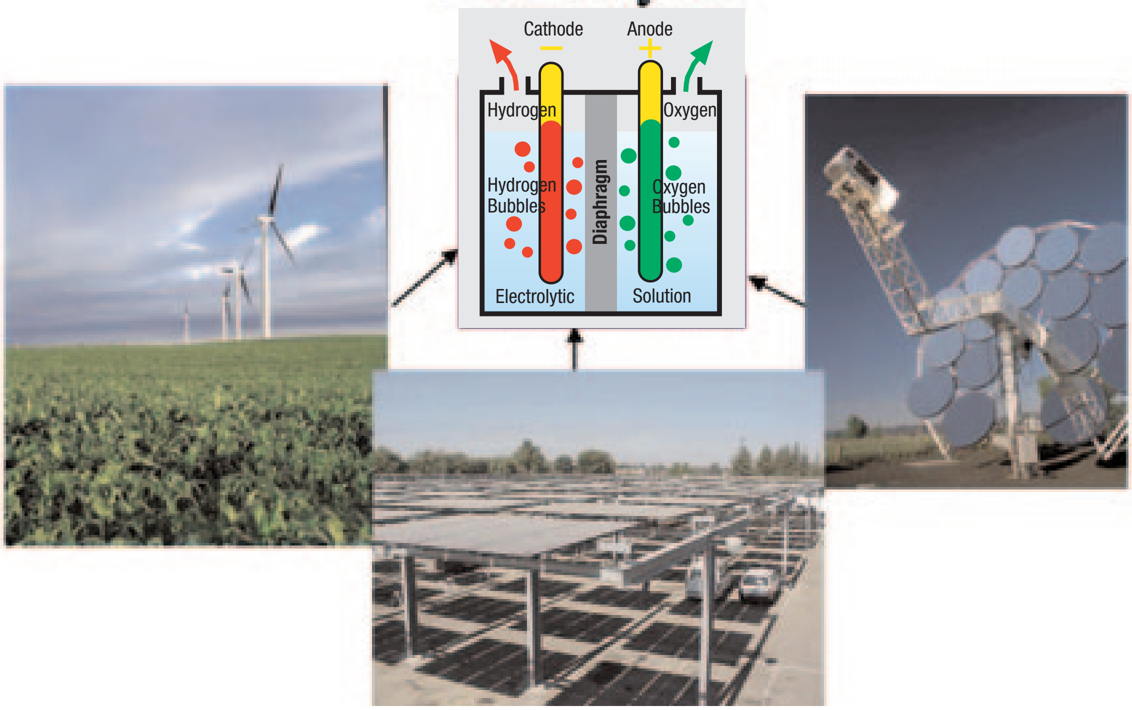
[53]Guerrant RL et al. “Diarrhea in developed and developing countries: magnitude, special settings, and etiologies” *Reviews of infectious disease,* 1990, 12:S41-S50.

[54]Estimating the Public Health Benefits of Proposed Air Pollution Regulations, Committee on Estimating Health-Risk-Reduction Benefits of Proposed Air Pollution Regulations, National Research Council, National Academies Press. 2002. http://books.nap.edu/books/0309086094/html/55.html#pagetop

[55]The Particulate-Related Health Effects of Reducing Power Plant Emissions, ABT Associates Inc., October 2000, http://www.abtassoc.com/reports/particulate-related.pdf

[56]Environmental Health Perspectives Volume 109, Supplement 3, June 2001 Assessing the Health Benefits of Urban Air Pollution Reductions Associated with Climate Change Mitigation (2000-2020): Santiago, São Paulo, México City, and New York City Luis Cifuentes, Victor H. Borja-Aburto, Nelson Gouveia, George Thurston, and Devra Lee Davis

# Renewable $H_2$ Production via Electrolysis




# HYDROGEN FACILITIES AND GOOD TO EXCELLENT RENEWABLE ENERGY RESOURCES