Biggest Challenge for the Hydrogen Economy
Hydrogen Production & Infrastructure Costs

Presentation to the
Aspen Global Change Institute

Long-Term Technology Pathways to Stabilization of
Greenhouse Gas Concentrations

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Presentation Overview

Background

- SFA Pacific’s background with the “hydrogen economy”
- Why hydrogen as a fuel?
- Current commercial H$_2$ manufacturing, transportation & markets

H$_2$ for power generation - the easy one

SFA Pacific’s recent screening studies of H$_2$ production &
infrastructure costs for fuel cell vehicles (FCV) - the hard one

- Auto & oil companies
- National Academies Hydrogen Committee

The hydrogen economy: challenges, issues, & uncertainties

Conclusions
Background of Recent SFA Pacific H₂ & CO₂ Mitigation Related Projects & Presentations

Private industry sponsored analyses

• Major private Multisponsored analyses of H₂, syngas & gas-to-liquids
• Major private Multisponsored analysis of CO₂ mitigation options
• CO₂ capture & storage analysis for the BP led CO₂ Capture Project (CCP) & the TransAlta led Canadian Clean Power Coalition (CCPC)
• H₂ production & infrastructure costs for major auto & oil companies
• Lead author on H₂ for the CO₂ capture section of the special IPCC report on geologic storage of CO₂

Most of our H₂ & CO₂ work is for industrial energy companies

SFA Pacific work on H₂ for fuel cell vehicles

SFA Pacific was part of the team that developed the road map for the California Fuel Cell Partnership in 2000

Nine major auto & oil companies interested in fuel cell vehicles + associated hydrogen production & infrastructure formed the International Hydrogen Infrastructure Group (IHIG) in 2001

• The IHIG contacted SFA Pacific originally in 2001 & again in 2002 requesting a screening analysis estimate of hydrogen production & infrastructure costs to support FC vehicles
• Due to secondary cost sharing by U.S. DOE via NREL our IHIG analysis was made public in July 2002 as report NREL/SR-540-32525

NREL report lead to a project for the National Academies H₂ Committee to develop an improved H₂ cost screening model
Background - Why Hydrogen as a Fuel?

Hydrogen is the most abundant element in the universe
When used as a fuel $\text{H}_2$ produces only clean energy & $\text{H}_2\text{O}$

Energy futurists see a logical progression from wood to coal to oil to NG to $\text{H}_2$ as standard of living & technologies improve

- Each fuel switch is cleaner, more efficient & lower in CO$_2$ emissions

Energy futurists also like $\text{H}_2$ from sustainable renewables

- However, $\text{H}_2$ from fossil fuels is cheaper until the fossil fuel age peaks in 50-100 years making fossil fuels increasingly more expensive

The hydrogen economy concept is quite interesting, long-term

- However, the short-term challenge is developing a hydrogen infrastructure while $\text{H}_2$ from fossil fuels is cheaper than renewables

Hydrogen Has Some Inherent Problems as It Is Not a Fuel Source, Merely an Energy Carrier

Like electricity, $\text{H}_2$ is not a naturally occurring fuel as NG & coal
Like electricity, $\text{H}_2$ production is expensive & inefficient
Like electricity, $\text{H}_2$ transport & storage is expensive & difficult

$\text{H}_2$ has the lowest energy density of any energy carrier

- High costs or heavy containers to improve $\text{H}_2$ energy density
  - Over 65 kg container weight per 1 kg gaseous or hydrate hydrogen
  - Even as expensive liquid $\text{H}_2$ still only 27% energy density of gasoline

$\text{H}_2$ is dangerous to use - big explosive range & invisible flame

- Current codes for $\text{H}_2$ use & storage are onerous

$\text{H}_2$ use is inefficient due to the large water formation & energy loss in the flue gas - LHV/HHV is 84.6% or 15.4% HHV losses
Fuel Cells and CO₂ Emissions Avoidance: The Key Drivers for the Hydrogen Economy

Fuel cells are unique in their direct conversion of chemical energy to electricity at low temperature & can be reversible

- However, exploiting these exciting attributes of fuel cells hinges on developing cost effective H₂ production & H₂ infrastructure

The global warming issue is likely the essential bridge to begin developing the long-term hydrogen economy

- Assuming global warming becomes a serious problem & we have the “stomach” to address the honest costs of effective CO₂ mitigation

Although H₂ from renewables is “politically” more correct & essential for the long-term, it is likely more economical to make H₂ from fossil fuels even with CO₂ capture & storage in the short-term

Hydrogen is Already a Large, Commercially Well Proven Industry

World commercial H₂ production is currently >40 billion scf/d

- Equivalent to 133,000 MWₜ or 75,000 MWₑ if converted to electricity

Most H₂ is made from natural gas via steam methane reforming however, 15% is from more capital intensive gasification

H₂ transportation & storage depends on amount & distance

- Pipelines for big users - worldwide over 10,000 miles with many in the U.S., longest is 250 miles from Antwerp to Normandy @ 100 atm.
- Liquid hydrogen for moderate users - used throughout California
- High pressure tube trailers for small users - used throughout the world

Many H₂ advocates are unaware of this impressive experience
Economics Beats Technology, Every Time

If the hydrogen economy is to develop within 50 years:

- The most cost effective options must be pursued for the two major energy & CO2 applications - transportation fuels & electric power
- Major infrastructure challenges must be objectively addressed

Hydrogen economy will likely require:

- Some form of subsidies or incentive to support developing the infrastructure, however, any subsidies should be non-discriminatory, transparent & performance-based to foster the lowest cost options

Hydrogen advocates must realize this may begin via H₂ from fossil fuels with CO₂ capture & storage if it is cheapest

- The key issue is getting H₂ infrastructure started, not waiting until H₂ from renewables becomes more competitive in 50-100 years
Power Generation Will Be Forced to Meet a Disproportionate Share of Any CO₂ Reductions

Transportation fuel users have more votes than CO₂ intensive industries as demonstrated in June 2000 in the U.S. & Europe

Power plants can not move to China, as other CO₂ intensive industries in Annex 1 nations will, if faced with carbon taxes

Large potential for improvements in power generation
- Increase old coal-boiler power plants efficiency - NG/CGCC repowering
- Replace coal with: co-firing biomass, natural gas or wind turbines
- New NGCC or CGCC - central power plant & especially cogeneration

Large point sources of power generation reduces both CO₂ mitigation & especially CO₂ capture/storage costs
**H₂ based Power Generation with CO₂ Storage**

This is the easier application because

- It can develop without any changes in existing energy infrastructure & does not have to wait for advanced fuel cells to commercially develop
- Large existing coal-fired power plants are most interesting due to their old age, high emissions & low efficiency - life-extended “big dirties”

Gasification repowering old coal units with H₂-CC is best

- Can increase both capacity & efficiency while at the same time reducing all existing traditional emissions plus Hg & CO₂ to near zero
- Perhaps the only major CO₂ capture & storage application that can make this important claim
- Also important as this helps obtain critical public & NGO support required for CO₂ capture/storage plus starts low-cost H₂ infrastructure

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**Hydrogen based Transportation**

This is a much bigger challenge than H₂ based electricity

- Requires major changes in existing energy infrastructure
- Delayed until mass production commercialization of fuel cell vehicles
- H₂ is expensive to distribute & store at high energy density
- If $/gal gasoline equivalent of H₂ (at the pump) is more than gasoline, average consumers will likely not buy FC vehicles

The “big bang” or “chicken & egg” problem:

- Before the first mass-produced fuel cell vehicles (FCV) roll off the assembly lines, much of the basic H₂ infrastructure & especially minimal H₂ dispensing & production must be in place
- These large H₂ capital investments face poor utilization (low annual load factors) for 10-20 yrs of ramp-up until there are large FCV fleets
Useful H₂ Conversions for Fuel Cell Vehicles

FCV requirements for 1 fill-up/week of 4 kg H₂ for good range

- Assuming 55 miles per kg H₂ & 12,000 miles per year
- Thereby average H₂ use is only 0.024 kg/hr or 0.8 kWh

1 kg of hydrogen contains the same useful (LHV) energy content as 1 U.S. gallon of gasoline: 113,800 Btu or 33.3 kWh

- Therefore $/kg H₂ is the same as $/gal gasoline energy equivalent
- However, watch out for H₂ FCV promoters who think since FCV will require less fuel H₂ price should shows as half of its real costs
- 100 MW, H₂ = 30 MM scf/d = 3,000 kg/hr: supports 125,000 FCV

Small gas stations dispenses 100,000 gal/mo. with >50% during 4 hrs of morning/evening commute 5 day/wk or 80 hrs/mo.

- If 100% H₂, 137 kg/hr av. & max peak storage x 3 - supports 5,700 FCV

Hydrogen Production & Distribution

Specific Technical Challenges & Issues

H₂ production & storage are both capital & energy intensive

- If fossil fuels require high temperatures processes & only 50-65% net efficiency when fuel for both H₂ production & electricity are included
- Electrolysis H₂ is 50 kWh/kg H₂ just power costs + high capital costs
  - Net efficiency of only 25-30% & very high CO₂ emissions for current grip
- Renewable problem of going though electrolysis plus low load factors

H₂ compressors are very expensive

- Generally water cooled positive displacement compressors at only 3 compression ratios per stage (high pressure H₂ requires 3-5 stages)
  - Thereby, high capital of $2,000 - 4,000/kW unit costs & high O&M

H₂ dispenser - a metering challenge due to changing pressures, temperatures & flow rates of this compressible gas at fill-ups
Hydrogen Distribution Options

H₂ Pipelines for Large H₂ Demands
- At $0.5 - 1.5 million/mile pipeline costs requires major H₂ flow rates & strategic locations for minimal total miles to be cost effective

Cryogenic Liquid H₂ Tankers for Medium H₂ Demands
- About 4,000 kg per tanker truck current technology favors small to moderate H₂ flows and long distances distribution
- At 10 kWh/kg H₂ power requirements, economics are greatly impacted by electric power costs

Small onsite H₂ generation avoids distribution
- However, pay higher commercial natural gas and power rates which are about 60-70% higher than industrial rates
- Like distributed power generation, permitting costs can be onerous

Hydrogen Economics for Fuel Cell Vehicles
No road tax, 18%/yr capital charges, current technology & energy prices
Central Facility - 60 MM scf/d H₂ (201 MWth) design to service 225,000 FCV & supply 411 stations with 329 kg/d per station
Onsite (Forecourt) - 470 kg/d design to service 550 FCV & supply 329 kg/d

- Electrolysis Onsite
- NG Onsite
- Electrolysis - Liq H₂
- Biomass - Liq H₂
- Coal - Liq H₂
- Residue - Liq H₂
- NG - Pipeline H₂
- NG - Tube H₂
- NG - Liq H₂

$/kg H₂ or $/U.S. gallon gasoline energy equivalent

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Hydrogen Production & Distribution
Basic Challenges & Issues

Classic “chicken and egg” or “big bang” ramp-up issue
- Previous H$_2$ costs assuming 90% annual load factors which will thereby support about 225,000 FCV
  - How many years will it take of one region to ramp-up to this small level?
  - All FCV could not go to just 1 or 2 onsite station during regional ramp-up
  - Low annual load factors for 5-10 years could double capital charges

Basic Challenges
- NFPA 50 A&B H$_2$ fire codes are onerous - many expenses & limitations
- Renewable wind turbine or PV based H$_2$ is very expensive due to low annual load factors & having to utilize electrolysis @ same low load
- Biomass gasification H$_2$ is expensive due to high fuel cost, challenges to make N$_2$-free, pure H$_2$ (not N$_2$-rich CH$_4$) & lack of economy of scale

Longer Term H$_2$ Challenges Yet to Resolve

H$_2$ from renewables & biomass is expensive
- Except for “opportunity” waste biomass which is quite limited, biomass requires cheap land & cheap labor to avoid high fuel costs
- Solar & wind have high power costs due to low annual load factors & the ultra high power requirements of electrolysis even at higher loads

Small may be beautiful but usually not cheap, efficient or clean
- Just look at the results of distributed power generation promotions, projects & technology developments over the last 10 years

H$_2$ via electrolysis have a very fundamental problem
- If cheap, efficient & clean enough power for a electrolysis H$_2$ future, we are likely much better off moving toward on an all electric society & advanced batteries to avoid the double energy conversion penalties
Ideas to Improve H₂ Economics

Co-production electric power for sales to the grid plus some H₂

- Questionable with forecourt H₂-FC due to high marginal O&M costs
- However, great for large central coal or refinery residue gasification due to the low marginal O&M costs & economy of scale benefits

Improve biomass based H₂ via black liquor gasification to H₂ plus co-gasifying biomass wastes or urban/industrial wastes in any nearby large coal or coke gasification to H₂ units

Low marginal cost for CO₂ capture for fossil H₂ - issue is the geologic storage of massive CO₂ amounts for many years

Reduce H₂ distribution costs via H₂ pipelines with utility status, convert existing natural gas pipelines back to a H₂/CH₄ mixture (town gas) & improved liquid H₂ designs

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Ideas to Improve H₂ Economics

Reduced H₂ filling station costs

- Decrease total stations & increase sales/station - clearly favors FCV equipped with smart computer GPS system to limit number of stations
- Filling vehicles with 4-6 small mobile LPG-type H₂ sphere or innovative way to change-out entire larger pre-filled tanks - just weigh H₂

Improved steam methane reformers & autothermal reformers

- Add secondary O₂ ATM to uprate existing SMR, if new: compact reformers, heat exchange SMR/ATR & ceramic membrane oxygen ATR

Improved gasification

- Simple, higher pressure & more efficient - two stage slurry solids with pitch or liquid CO₂, partial heat recovery, sour shift for single cooling

Innovative uses of liquid H₂ throughout the entire system

- Production, distribution, storage, dispensing & even into FCV
Overcoming the “Big Bang” $H_2$ Ramp-up Issue

The coal gasification $H_2$ power plant 500 MWe = 800 MW$_{th}$ $H_2$

- $CO_2$ capture & storage plus small $H_2$ liquefaction & storage (tank to fill during lower power demand) & used as $H_2$ is needed during ramp-up
- Distribute this liquid $H_2$ to fuel cell vehicle filling stations for the small but growing transportation $H_2$ requirements, as needed during ramp-up
- Power losses to $H_2$ are minor & can be easily made-up by other power plants or if peak power problems just add some NG to existing $H_2$ - CC

Will require subsidies to encourage $H_2$ & $CO_2$ storage

- Less than currently given renewable power & ethanol in gasoline
- Current wind turbine subsidy of $18/MWh - when wind power replaces NGCC @ 0.36 ton $CO_2$/MWh, the $CO_2$ avoidance subsidy is $50/ton CO_2$
- Current ethanol subsidy of $0.53/gal or $6.94/MM Btu LHV - if given any $CO_2$ free $H_2$ source would be a subsidy of $0.79/kg H_2$

Conclusions

Hydrogen has some inherent problems as it is not an energy source, merely an energy carrier with low energy density

- Nevertheless, the hydrogen economy is interesting due to unique attributes relative to fuels cells & the global warming issue

The hydrogen economy favors $H_2$ from fossil fuel with $CO_2$ capture & storage as this is cheaper than $H_2$ from renewables

- Hydrogen for power generation via coal gasification repowering of old, coal units is the place to start as this avoids infrastructure problems
- Hydrogen for fuel cell vehicles is a greater challenge due to the “big bang” hydrogen infrastructure & vehicles/fuel ramp-up problems
  - However that can be reduced by extracting hydrogen “as needed” from large hydrogen based coal gasification power plants co-feeding biomass
- Will require subsidies, however, less than currently given to renewable power & ethanol in gasoline with much greater social benefits