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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by

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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

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Background of Recent SFA Pacific H_2 & CO_2 Mitigation Related Projects & Presentations

Private industry sponsored analyses

- Major private Multisponsored analyses of H_2, syngas & gas-to-liquids
- Major private Multisponsored analysis of CO_2 mitigation options
- CO_2 capture & storage analysis for the BP led CO_2 Capture Project (CCP) & the TransAlta led Canadian Clean Power Coalition (CCPC)
- H_2 production & infrastructure costs for major auto & oil companies
- Lead author on H_2 for the CO_2 capture section of the special IPCC report on geologic storage of CO_2

Most of our H_2 & CO_2 work is for industrial energy companies

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SFA Pacific work on H_2 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 H_2 Committee to develop an improved H_2 cost screening model

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Background - Why Hydrogen as a Fuel?

Hydrogen is the most abundant element in the universe

When used as a fuel H_2 produces only clean energy & H_2O

Energy futurists see a logical progression from wood to coal to oil to NG to H_2 as standard of living & technologies improve

- Each fuel switch is cleaner, more efficient & lower in CO_2 emissions

Energy futurists also like H_2 from sustainable renewables

- However, 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 H_2 from fossil fuels is cheaper than renewables

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

Like electricity, H_2 is not a naturally occurring fuel as NG & coal

Like electricity, H_2 production is expensive & inefficient

Like electricity, H_2 transport & storage is expensive & difficult

H_2 has the lowest energy density of any energy carrier

- High costs or heavy containers to improve H_2 energy density
  - Over 65 kg container weight per 1 kg gaseous or hydrate hydrogen
  - Even as expensive liquid H_2 still only 27% energy density of gasoline

H_2 is dangerous to use - big explosive range & invisible flame

- Current codes for H_2 use & storage are onerous

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

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Fuel Cells and CO_2 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 H_2 production & H_2 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 CO_2 mitigation

Although H_2 from renewables is "politically" more correct & essential for the long-term, it is likely more economical to make H_2 from fossil fuels even with CO_2 capture & storage in the short-term

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Hydrogen is Already a Large, Commercially Well Proven Industry

World commercial H_2 production is currently >40 billion scf/d

- Equivalent to 133,000 MW_t or 75,000 MW_e if converted to electricity

Most H_2 is made from natural gas via steam methane reforming however, 15% is from more capital intensive gasification

H_2 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 through out California
- High pressure tube trailers for small users - used through out the world

Many H_2 advocates are unaware of this impressive experience

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Farmland in Kansas - Commercial (no subsidies) Coke to H_2 Gasification Plant for Ammonia & CO_2

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 H_2 from fossil fuels with CO_2 capture & storage if it is cheapest

- **The key issue is getting H_2 infrastructure started, not waiting until H_2 from renewables becomes more competitive in 50-100 years**

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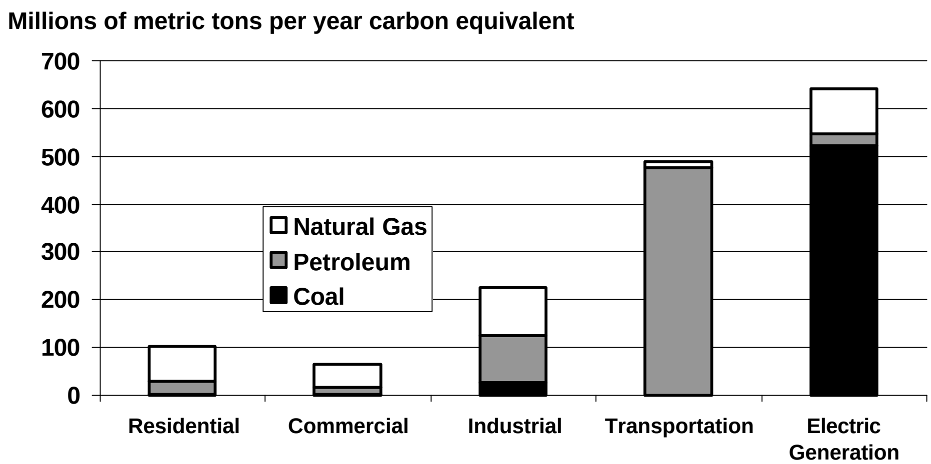
United States CO_2 Emissions by Sector and Fuels in 2000



Source: U.S. EPA Inventory of Greenhouse Gas Emissions, April 2002

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Power Generation Will Be Forced to Meet a Disproportionate Share of Any CO_2 Reductions

Transportation fuel users have more votes than CO_2 intensive industries as demonstrated in June 2000 in the U.S. & Europe

Power plants can not move to China, as other CO_2 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 CO_2 mitigation & especially CO_2 capture/storage costs

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H_2 based Power Generation with CO_2 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 H_2-CC is best

- Can increase both capacity & efficiency while at the same time reducing all existing traditional emissions plus Hg & CO_2 to near zero
- Perhaps the only major CO_2 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 H_2 infrastructure

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Hydrogen based Transportation

This is a much bigger challenge than H_2 based electricity

- Requires major changes in existing energy infrastructure
- Delayed until mass production commercialization of fuel cell vehicles
- H_2 is expensive to distribute & store at high energy density
- If $/gal gasoline equivalent of H_2 (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 H_2 infrastructure & especially minimal H_2 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

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Useful H_2 Conversions for Fuel Cell Vehicles

FCV requirements for 1 fill-up/week of 4 kg H_2 for good range

- Assuming 55 miles per kg H_2 & 12,000 miles per year
- Thereby average H_2 use is only 0.024 kg/hr or 0.8 kWh_t

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_t

- Therefore \$/kg H_2 is the same as \$/gal gasoline energy equivalent
- However, watch out for H_2 FCV promoters who think since FCV will require less fuel H2 price should shows as half of its real costs
- 100 MW_t H_2 = 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% H_2, 137 kg/hr av. & max peak storage x 3 - supports 5,700 FCV

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Hydrogen Production & Distribution Specific Technical Challenges & Issues

H_2 production & storage are both capital & energy intensive

- If fossil fuels require high temperatures processes & only 50-65% net efficiency when fuel for both H_2 production & electricity are included
- Electrolysis H_2 is 50 kWh/kg H_2 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

H_2 compressors are very expensive

- Generally water cooled positive displacement compressors at only 3 compression ratios per stage (high pressure H_2 requires 3-5 stages) Thereby, high capital of \$2,000 - 4,000/kW unit costs & high O&M

H_2 dispenser - a metering challenge due to changing pressures, temperatures & flow rates of this compressible gas at fill-ups

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Hydrogen Distribution Options

H_2 Pipelines for Large H_2 Demands

- At $0.5 - 1.5 million/mile pipeline costs requires major H_2 flow rates & strategic locations for minimal total miles to be cost effective

Cryogenic Liquid H_2 Tankers for Medium H_2 Demands

- About <u>4,000 kg per tanker truck</u> current technology favors small to moderate H2 flows and long distances distribution
- At 10 kWh/kg H_2 power requirements, economics are greatly impacted by electric power costs

Small onsite H_2 generation <u>avoids</u> 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

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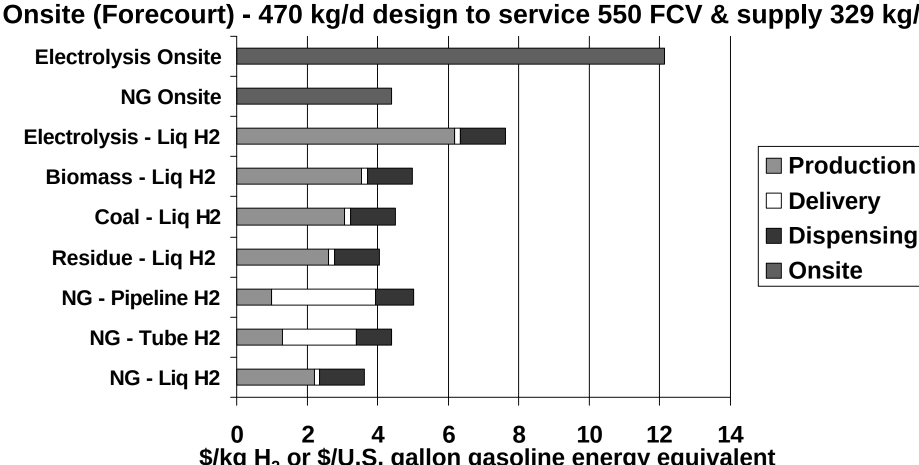
Hydrogen Economics for Fuel Cell Vehicles

No road tax, 18%/yr capital charges, current technology & energy prices

Central Facility - 60 MM scf/d H_2 (201 MW_{th}) design to service 225,000 FCV & supply 411 stations with <u>329 kg/d per station</u>

Onsite (Forecourt) - 470 kg/d design to service 550 FCV & supply 329 kg/d



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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

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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 <u>not</u> 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

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Ideas to Improve H_2 Economics

Co-production electric power for sales to the grid plus some H_2

- Questionable with forecourt H_2-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 H_2 via black liquor gasification to H_2 plus co-gasifying biomass wastes or urban/industrial wastes in any nearby large coal or coke gasification to H_2 units

Low marginal cost for CO_2 capture for fossil H_2 - issue is the geologic storage of massive CO_2 amounts for many years

Reduce H_2 distribution costs via H_2 pipelines with utility status, convert existing natural gas pipelines back to a H_2/CH_4 mixture (town gas) & improved liquid H_2 designs

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Ideas to Improve H_2 Economics

Reduced H_2 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 H_2 sphere or innovative way to change-out entire larger pre-filled tanks - just weigh H_2

Improved steam methane reformers & autothermal reformers

- Add secondary O_2 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 CO_2, partial heat recovery, sour shift for single cooling

Innovative uses of liquid H_2 through out the entire system

- Production, distribution, storage, dispensing & even into FCV

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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

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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

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