

Alternative Technologies and Strategies for Hydrogen Production

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OUTLINE OF PRESENTATION

- Context for considering H₂ production technologies and strategies
- Focus on centralized H₂ production options for the long term (> 2020) characterized by zero or near-zero lifecycle CO₂ emissions:
 - H₂ from water via electrolysis and renewable electricity (*future technologies*)
 - H₂ from water via complex thermochemical cycles using nuclear heat from high-temperature gas-cooled reactors (*future technologies*)
 - H₂ from natural gas via steam reforming (*current technology*) with geological sequestration of separated CO₂
 - H₂ from coal via gasification (*current technology*) with geological sequestration of separated CO₂
- Outlook for geologic sequestration of CO₂
- How much is it worth to find out (*soon*) if geological sequestration is viable at large scales?

CONTEXT FOR H₂ AS ENERGY CARRIER

- Hydrogen's main attractions as energy carrier:
 - Potential for near-zero fuel cycle emissions of GHGs
 - Zero or near-zero emissions of air pollutants
 - Energy supply security
- Near-zero GHG emission goal realizable only via:
 - H₂ from H₂O via electricity or heat from carbon-free primary energy
 - H₂ from biomass
 - H₂ from fossil fuels + CO₂ capture/storage...in large-scale plants
- Main goals for near-term (*next ~ 10-20 y*):
 - Demonstration of H₂ production from fossil fuels with near-zero emissions of GHGs (*FutureGen*)
 - Market launch of H₂ vehicles (*FreedomCar*)
 - Embryonic H₂ refueling infrastructure development (*FreedomFuel*)
- Near-term supply will be merchant H₂, electrolytic H₂ via offpeak electricity, or steam methane reforming at refueling stations
- Least costly long-term options for H₂ with near-zero GHG emissions?

CENTRALIZED H₂ PRODUCTION OPTIONS

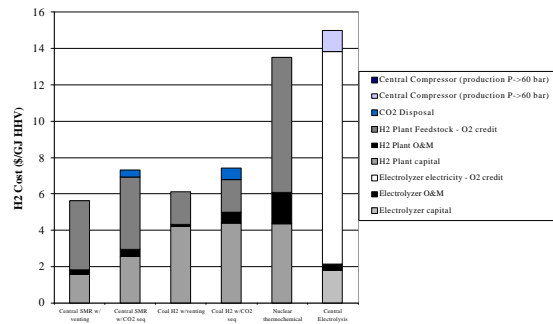
(*Long-term—beyond 2020*)

- Advanced electrolysis via low-C or zero-C electricity sources
- Complex thermochemical cycles using nuclear heat from high-T gas-cooled reactor
- Steam reforming of natural gas—with underground storage of separated CO₂
- Coal gasification—with underground storage of separated CO₂

PLANT-GATE H₂ PRODUCTION COSTS

Current NG, coal technologies (2005 fuel prices),
Future nuclear, renewable technologies

($P_{NG} = \$3.1/\text{GJ}$; $P_{COAL} = \$1.2/\text{GJ}$; $P_{NUC.HEAT} = 1.6 \text{ ¢/kWh}_h$; $P_{RENEW.ELECT} = 4.0 \text{ ¢/kWh}_e$)



CENTRALIZED ELECTROLYTIC H₂ PRODUCTION USING ADVANCED TECHNOLOGY

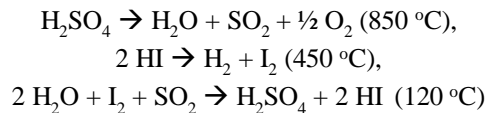
(500 MW_h @ 60 bar, electricity @ 4.0 ¢/kWh)

Technology	Targets for capital cost/performance			Plantgate cost breakdown (\$/GJ, HHV basis)				
				Electrolysis		Other costs/credits		Total cost
	Capital (\$/kW _h)	P (bar)	η (%)	Cap, O&M	Electricity	Comp	O ₂ Credit	
Lo P, Lo T	\$300	2	83	2.14	13.39	1.16	- 1.54	15.2 (\$2.2 gge)
Hi P, Lo T	\$400	31	80	2.85	13.89	0.16	- 1.54	15.4 (\$2.2 gge)
Lo P, Hi T	\$900	2	111	6.42	10.01	1.16	- 1.54	16.1 (\$2.3 gge)

gge = gallons of gasoline equivalent energy

THERMOCHEMICAL H₂ FROM H₂O USING NUCLEAR OR SOLAR HEAT

- Direct H₂O dissociation requires T ~ 4000 °C
- Complex thermochemical cycles being developed—e.g., S-I process at General Atomics:

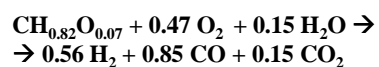


- $\zeta \leq 50\%$
- Consider 1200 MW_h H₂ production plant (*heat from modular helium reactor*):
- Projected costs:
 - \$1.3/gge for nuclear heat ~ 1.6 ¢/kWh_l (*compared to ~ 4.2 ¢/kWh_e for electricity*), for $\eta = 50\%$
 - **Total hoped for cost for future nuclear thermochemical H₂ ~ \$2.0/gge**
- For comparison, **total cost = \$1.1/gge for coal H₂ w/CO₂ capture and storage (commercial technology)**
- Solar heat-based processes not less costly than nuclear

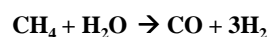
MAKING H₂ FROM FOSSIL FUELS

Begin with "Syngas" Production:

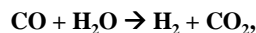
Oxygen-Blown Coal Gasification:



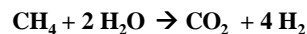
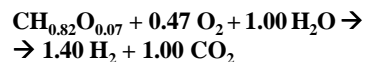
Steam-Reforming of Natural Gas



Followed by Syngas Cooling & Water-Gas Shift Reaction:



Net Effect:



Followed by CO₂/H₂ Separation via Physical or Chemical Process

HHV efficiency [(H₂ output)/(Total primary fuel input)]:

~ 70% for coal

~ 80% for natural gas

Separated CO₂ Can Be Disposed of at Relatively Low Incremental Cost

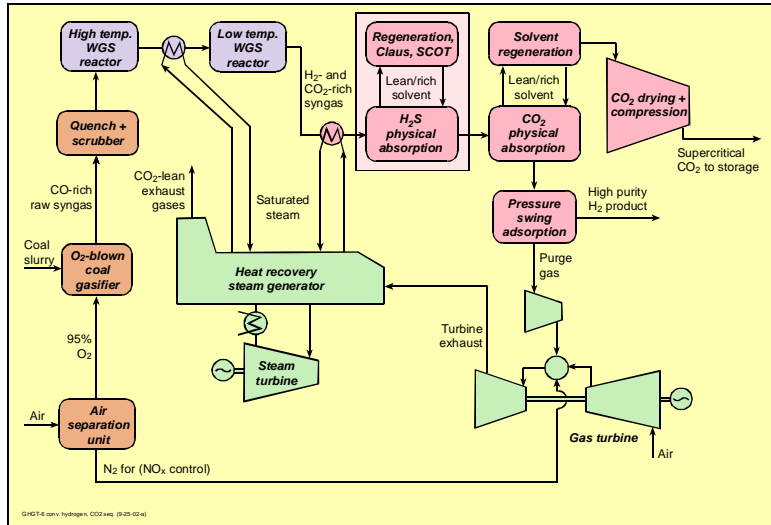
H₂ FROM NATURAL GAS VIA STEAM REFORMING

- H₂ not yet used as energy carrier
- But H₂ use in chemical/refining industries ~ 1% of global energy (~ 40 million tonnes/y)
- In most parts of world H₂ made from natural gas via steam reforming
 - At 2005 NG price for electric generators in US (\$3.1/GJ), H₂ cost is ~ \$5.6/GJ (\$0.81/gge) for large (1 GW_h) plant with CO₂ venting [conversion efficiency ~ 81% (HHV basis)]
 - With CO₂ capture and storage [100 km transport to underground storage site (saline aquifer 2 km underground)] cost increases to \$7.3/GJ (\$1.05/gge) and efficiency falls to 78%
- Concerns about natural gas:
 - Rising prices
 - Price volatility
 - Limited North American supplies
- What about H₂ from coal?
 - Proven technology
 - China (producing 5 million t/y of H₂, mostly for making NH₃) makes most of its H₂ via coal gasification

WHY COAL?

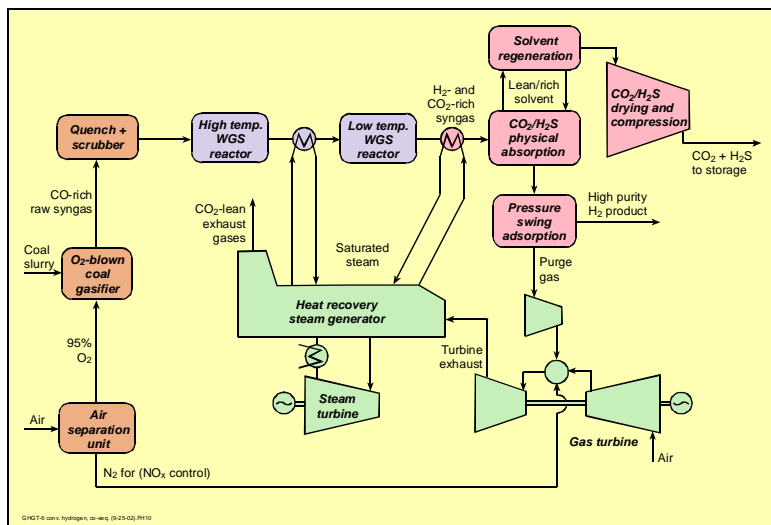
- Coal resources abundant globally
- Much of global population (e.g., China, India) heavily coal-dependent
- Coal prices low and not volatile
- H₂ via gasification:
 - Secure alternative to oil for transportation
 - near-zero emissions of air pollutants/GHGs
 - Attractive costs for coal-derived H₂ with CO₂ capture/storage...competitive with H₂ from natural gas with CO₂ venting when natural gas price reaches ~ \$4/GJ
- Residual environmental, health, safety problems of coal mining

Capture (and Co-store) H_2S with CO_2



- Remove the traditional acid gas recovery (AGR) unit.

Conventional H_2 Production with CO_2/H_2S Capture



- Resulting system is simpler and cheaper...cost reduced to \$6.7/GJ (\$0.97/gge).

**CONSUMER FUEL COSTS: GASOLINE ICE
CARS AND H₂ FUEL CELL CARS**
(excluding retail fuel taxes)

Energy carrier	Fuel cost, ¢/gallon, gasoline equivalent		Fuel cost for driving, ¢ per mile (relative fuel cycle GHG)		
	Production cost	Cost to consumer	Gasoline		H ₂ FCV, 82 mpg, ¢/mi
			Current ICEV, 27 mpg	Advanced ICEV, 46 mpg	
Gasoline (US, 2000)	96	114	4.2 (1.00)	2.5 (0.59)	-
H ₂ from coal (CO ₂ vented)	89	231	-	-	2.8 (0.60)
H ₂ from coal (CO ₂ sequestered)	105	247	-	-	3.0 (0.07)

...But need to make full lifecycle cost comparison.

OPTIONS FOR CO₂ DISPOSAL

- Deep ocean disposal
- Disposal in geological media
 - Depleted oil and gas fields
 - Beds of unminable coal
 - **Deep saline aquifers** (at least 800 m down)
- Disposal as carbonate rocks

GLOBAL CAPACITY FOR CO₂ STORAGE IN DEEP SALINE AQUIFERS

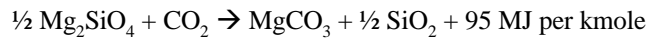
- **If closed aquifers with structural traps needed:** ~ 50 GtC
- **If large, open aquifers w/good top seals also usable:**
 - Estimate by IEA GHG R&D Programme: up to 2,700 GtC
 - Estimate by Hendriks (*Utrecht University*): ~ 13,000 GtC
- **For comparison:**
 - Cumulative emissions, 1990-2100, from fossil fuel burning [*Business-As-Usual Global Energy Scenario (IS92a) of IPCC: 1,500 GtC*]
 - Carbon content of remaining exploitable fossil fuels (*excluding methane hydrates*) ~ 5,000 – 7,000 GtC

CO₂ DISPOSAL EXPERIENCE

- **Enhanced oil recovery:** *74 projects worldwide injecting 30 MMt CO₂/y; 4% of US oil so produced—mostly using CO₂ from natural reservoirs (> 3000 km of CO₂ pipelines in US), but Weyburn (Canada) uses 1.5 MMt/y of CO₂ piped 300 km from North Dakota coal gasification plant*
- **Enhanced coal bed methane recovery:** *1 commercial project in San Juan Basin (US)*
- **Acid gas disposal:** *31 acid gas (H₂S + CO₂) disposal projects in Canada associated with recovery of sour NG*
- **Sleipner project in North Sea:** *1 MMt/y of CO₂ being disposed of since 1996 in aquifer under seabed*

SEQUESTERING CO₂ AS CARBONATE MINERAL

- Certain abundant minerals—e.g., forsterite (Mg₂SiO₄) or serpentine (Mg₃Si₂O₅(OH)₄)—can be reacted with CO₂ via exothermic reactions favored under ambient conditions. E.g., for olivine (MgSiO₄ – FeSiO₄):



- Advantages:
 - Resources abundant enough to store as carbonates carbon in all remaining recoverable fossil fuels
 - Absolutely safe disposal method
- Disadvantages:
 - Large amounts of material must be transported, processed, and stored [~ 6 tonnes mineral (e.g., *serpentine*) needed per tonne of coal processed]
 - Probably much more costly (\$/t CO₂) than disposing of supercritical CO₂ in deep saline aquifers

Competition in Making H₂ for Climate-Constrained World

- If underground storage of CO₂ proves to be viable in large-scale applications, fossil-fuel derived H₂ with underground storage of CO₂ coproduct will be much less costly than H₂ derived from carbon-free (*renewable or nuclear*) primary energy sources
- Coal-derived H₂ w/capture/storage competitive with natural gas-derived H₂ w/venting when P_{NG} ~ \$4.0/GJ
- Primary energy and production cost penalties for capture/storage are modest for coal (~ 4% and 19%, respectively, relative to CO₂ venting) outstanding (*long-term*) opportunity for coal

WHILE WAITING FOR A H₂ ECONOMY

- H₂ won't be widely used as energy carrier for at least 20-30 years
- But there are near-term opportunities for exploiting H₂ use in chemical/refining industries
- Gasification-based H₂ production at oil refineries plants (*via gasification of coke, pitch*) and NH₃ plants might be exploited as low-cost source of CO₂ for “megascale demonstration projects” of CO₂ storage in various geological media
 - Offering plant-gate CO₂ costs \leq \$6/t (~ \$0.3/Mscf) gasification-based H₂ production plants often competitive even with natural CO₂ supplies for EOR projects
 - Are suitable CO₂ storage demo sites near prospective industrial H₂ production sites?

Plant-Gate CO₂ Costs with CO₂ Capture

Plant type	Plant output	CO ₂ disposal rate (t/h)	Plant-gate CO ₂ cost (\$/t)
NG Combined Cycle Power	311 MW _e	118	58
Coal Ultracritical Steam Power	367 MW _e	335	33
NG-Derived H ₂	1000 MW _h	204	24
Coal IGCC Power	362 MW _e	301	15.6
Coal IGCC Power (co-store)	362 MW _e	301	10.6
Coal-Derived H ₂	1265 MW _h	554	6.1
Coal-Derived H ₂ (co-store)	1265 MW _h	554	0.5

Costs for CO₂ coproduct of H₂ produced at refineries via petroleum residuals gasification would be similar to those for coal systems.

**WHAT IS IT WORTH TO FIND OUT (SOON!)
IF GEOLOGICAL STORAGE OF CO₂ IS VIABLE?**

- Suppose that:
 - Sequestration is not viable; coal H₂ technology is not developed
 - H₂ can be produced indefinitely from abundant NG at costs for 2020 NG prices
 - Climate change concerns motivate levy of carbon tax at level sufficient to make renewable electrolytic H₂ or nuclear thermochemical H₂ competitive with H₂ from NG with CO₂ venting
- What would be required carbon tax?
 - ~ \$650/tC for renewable electrolytic H₂ [*such a tax would have increased US retail expenditures on energy almost 3X, from \$560 billion/y to \$1550 billion/y, at energy use level (97 Quads) and CO₂ emission level (1.52 GtC) for 1999*]
 - ~ \$420/tC for nuclear thermochemical H₂ [*which would have doubled US retail energy expenditures—to \$1200 billion/y (1999 energy use/CO₂ emission levels)*]
- For comparison, if sequestration turns out to be viable, the carbon tax needed to induce sequestration for coal-derived H₂ is ~ \$50/tC for deep aquifer disposal 100 km from conversion plant [*which would have increased US retail energy expenditures 13%—to \$630 billion/y (1999 energy use/CO₂ emission levels)*]