# Hydrogen Production Technologies/Strategies for Automotive Applications

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# OUTLINE OF PRESENTATION

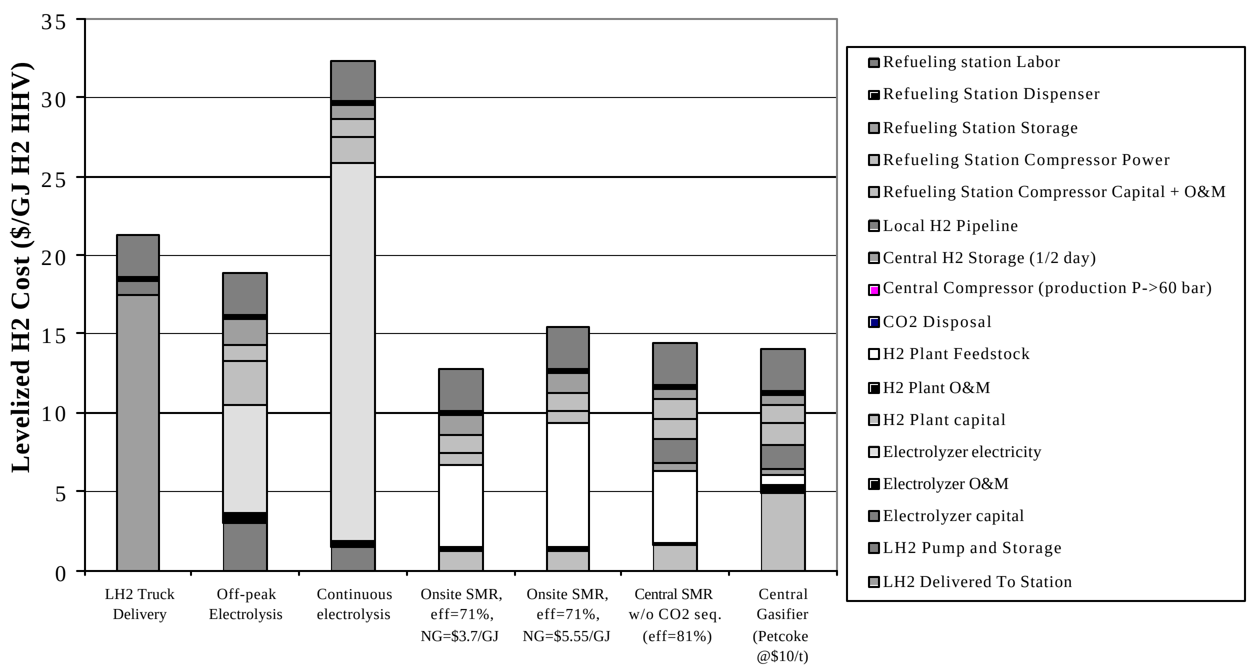
- Listing of medium-term (2010-2020) options for $H_2$ production and prospective costs
- Focus on centralized $H_2$ production options for the long term *(> 2020*) characterized by zero or near-zero lifecycle $CO_2$ emissions:
  - $H_2$ from natural gas via steam reforming and from coal via gasification (*current technology*) with geological sequestration of separated $CO_2$
  - $H_2$ from water via electrolysis and renewable electricity (*future technologies*)
  - $H_2$ from water via complex thermochemical cycles using nuclear heat from high-temperature gas-cooled reactors (*future technologies*)
- Outlook for geologic sequestration of $CO_2$
- How much is it worth to find out (soon) if geological sequestration is viable at large scales?

# $H_2$ PRODUCTION OPTIONS
(*Medium term—2010-2020*)

- Merchant $H_2$
- Production at Refueling Stations (*$10^6$ scf/d*)
  - Electrolysis [*using power @ 2 ¢/kWh (offpeak) or 6.9 ¢/kWh* (*ave commercial rate for 2020*)]
  - NG steam reforming (*using NG at ave commercial or industrial NG price for 2020*)
- Centralized Production (*e.g., at refineries*)
  - NG steam reforming (*using NG at ave NG price for electric generators in 2020*)
  - Petcoke gasification [*using petcoke @ $10/t ($0.35/GJ*)]

# RETAIL $H_2$ COSTS ~ 2010-2020

($P_{OFFPEAK.ELECT}$ = 2.0 ¢/kWh$_e$; $P_{COMMERCIAL.ELECT}$ = 6.9 ¢/kWh$_e$;
$P_{INDUSTRIAL.NG}$ = \$3.7/GJ; $P_{COMMERCIAL.NG}$ = \$5.55/GJ; $P_{PETCOKE}$ = \$0.35/GJ)



# CENTRALIZED $H_2$ PRODUCTION OPTIONS

(*Long-term—beyond 2020*)

- Steam reforming of natural gas—without and with sequestration of separated $CO_2$
- Coal gasification—without and with sequestration of separated $CO_2$
- Advanced electrolysis via low-C or zero-C electricity sources
- Complex thermochemical cycles using nuclear heat from high-T gas-cooled reactor

# MAKING $H_2$ FROM FOSSIL FUELS

*Begin with"Syngas" Production:*

***Oxygen-Blown Coal Gasification:***

$$CH_{0.82}O_{0.07} + 0.47\ O_2 + 0.15\ H_2O \rightarrow$$
$$\rightarrow 0.56\ H_2 + 0.85\ CO + 0.15\ CO_2$$

***Steam-Reforming of Natural Gas***

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

***Followed by Syngas Cooling & Water-Gas Shift Reaction:***

$$CO + H_2O \rightarrow H_2 + CO_2,$$

***Net Effect:***

$$CH_{0.82}O_{0.07} + 0.47\ O_2 + 1.00\ H_2O \rightarrow$$
$$\rightarrow 1.40\ H_2 + 1.00\ CO_2$$

$$CH_4 + 2\ H_2O \rightarrow CO_2 + 4\ H_2$$

***Followed by $CO_2/H_2$ Separation via Physical or Chemical Process***

**HHV efficiency [($H_2$ output)/(Total primary fuel input)]:**

**~ 70% for coal**

**~ 80% for natural gas**

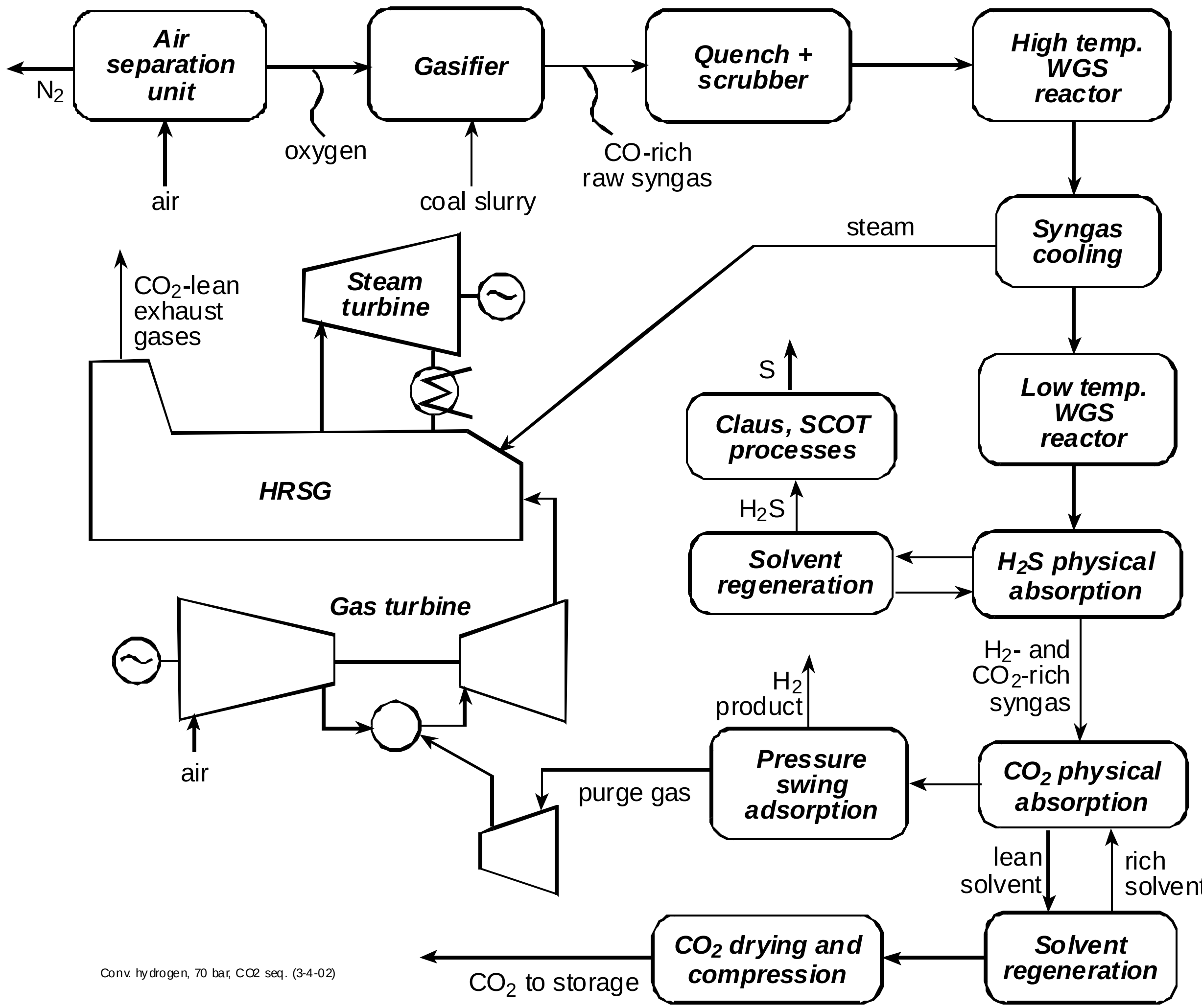
*Separated $CO_2$ Can Be Disposed of at Relatively Low Incremental Cost*

# WHY COAL?

- Coal resources abundant globally:
  - Recoverable coal ~ 200,000 EJ (*2000 y supply at current coal use rate; 580 y supply at current total fossil energy use rate*)
  - Recoverable natural gas:
    - Conventional ~ 12,000 EJ
    - Unconventional ~ 33,000 EJ
- Much of global population (*e.g.*, *China*, *India*) heavily coal-dependent
- Coal prices low [*1999 NG price for US electric generators = 2.1 X coal price; projected (2020) = 4.0 X coal price*]
- Coal prices not volatile
- Environmental issues ➔ need radical technological innovation
- Gasification → near-zero emissions of air pollutants/ GHGs
- Residual environmental, health, safety problems of coal mining

# $H_2$ Production with $CO_2$ Sequestration

## - Based on Commercial Technology -



# CONSUMER FUEL COSTS FOR GASOLINE ICE CARS AND $H_2$ FUEL CELL CARS

(*excluding retail fuel taxes*)

| Energy carrier | Fuel cost (*¢/gallon, gasoline equivalent*) | | Cost of driving a car (*¢ per mile*) | | |
|---|---|---|---|---|---|
| | Production cost | Cost to consumer | Gasoline | | $H_2$ FCV (*82 mpg, ge*) |
| | | | Current ICEV (*28 mpg*) | ICE/HEV (*48 mpg*) | |
| Gasoline (*US, 2000*) | 96 | 114 | 4.1 | 2.4 | - |
| $H_2$ from coal (*$CO_2$ vented*) | 85 | 193 | - | - | 2.4 |
| $H_2$ from coal (*$CO_2$ seq.*) | 108 | 218 | | | 2.7 |

# CENTRALIZED ELECTROLYTIC $H_2$ PRODUCTION USING ADVANCED TECHNOLOGY

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

| Tech-nology | 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 | Elec-tricity | Comp | $O_2$ Credit | Stor -age | |
| Lo P, Lo T | $300 | 2 | 83 | 2.14 | 13.39 | 1.16 | - 1.54 | 0.41 | 15.6 |
| Hi P, Lo T | $400 | 31 | 80 | 2.85 | 13.89 | 0.16 | - 1.54 | 0.41 | 15.8 |
| Lo P, Hi T | $900 | 2 | 111 | 6.42 | 10.01 | 1.16 | - 1.54 | 0.41 | 16.5 |

# THERMOCHEMICAL $H_2$ FROM $H_2O$ USING NUCLEAR OR SOLAR HEAT

- Direct $H_2O$ dissociation requires T ~ 4000 $^oC$
- Complex thermochemical cycles being developed—e.g., S-I process at General Atomics:

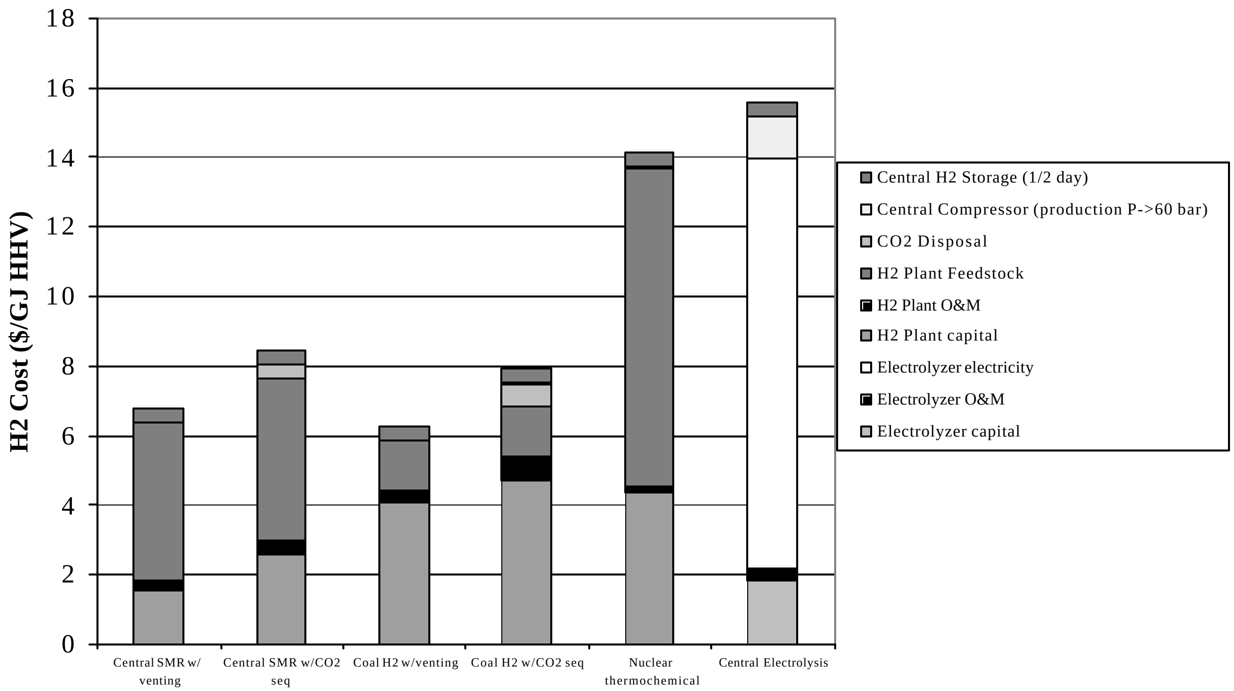
$$H_2SO_4 \rightarrow H_2O + SO_2 + \frac{1}{2} O_2 \ (850\ ^oC),$$
$$2\ HI \rightarrow H_2 + I_2 \ (450\ ^oC),$$
$$2\ H_2O + I_2 + SO_2 \rightarrow H_2SO_4 + 2\ HI \ (120\ ^oC)$$

- ? $\leq$ 50%
- Projected cost of nuclear heat from MHR ~ 1.6 ¢/$kWh_t$ compared to ~ 4.2 ¢/$kWh_e$ for electricity (*future technology*)➔ @ $\eta$ = 50%, nuclear contribution to $H_2$ cost = \$1.3/gge and total cost ~ \$2.0/gge…compared to total cost of \$1.1/gge for coal $H_2$ w/$CO_2$ sequestration (*commercial technology*)
- Solar heat-based processes not less costly than nuclear

# PLANT-GATE $H_2$ PRODUCTION COSTS

*Current NG, coal technologies (2020 fuel prices),*
*Future nuclear, renewable technologies*

($P_{NG}$ = \$3.7/GJ; $P_{COAL}$ = \$0.9/GJ; $P_{NUC.HEAT}$ = 1.6 ¢/kWh$_t$; $P_{RENEW.ELECT}$ = 4.0 ¢/kWh$_e$)



# OPTIONS FOR $CO_2$ 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 $CO_2$ 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, IS92a: 1,500 GtC
  - Carbon content of remaining exploitable fossil fuels (*excluding methane hydrates*) ~ 5,000 – 7,000 GtC

# $CO_2$ DISPOSAL EXPERIENCE

- **Enhanced oil recovery**: *74 projects worldwide injecting 30 MMt $CO_2$/y; 4% of US oil so produced—mostly using $CO_2$ from natural reservoirs (> 3000 km of $CO_2$ pipelines in US), but Weyburn (Canada) uses 1.5 MMt/y of $CO_2$ 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 ($H_2S$ + $CO_2$) disposal projects in Canada associated with recovery of sour NG*
- **Sleipner project in North Sea:** *1 MMt/y of $CO_2$ being disposed of since 1996 in aquifer under seabed*

# WHAT IS IT WORTH TO FIND OUT (<u>SOON</u>!) IF GEOLOGICAL SEQUESTRATION IS VIABLE?

- Suppose that:
  - Sequestration is not viable; coal $H_2$ technology is not developed
  - $H_2$ 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 $H_2$ or nuclear thermochemical $H_2$ competitive with $H_2$ from NG with $CO_2$ venting
- What would be required carbon tax?
  - ~ $650/tC for renewable electrolytic $H_2$ [*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* $CO_2$ *emission level (1.52 GtC) for 1999*]
  - ~ $420/tC for nuclear thermochemical $H_2$ [*which would have doubled US retail energy expenditures—to $1200 billion/y (1999 energy use/*$CO_2$ *emission levels*)]
- For comparison, if sequestration turns out to be viable, the carbon tax needed to induce sequestration for coal-derived $H_2$ is ~ $50/tC for deep aquifer disposal 100 km from conversion plant [*which would have increased US retail energy expenditures 13%—to $630 billion/y (1999 energy use/*$CO_2$ *emission levels*)]