Co-Production of Hydrogen and Electricity from Fossil Fuels with CO_2 Capture

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Large-Scale Production of H_2 from Fossil Fuels

Four Related Papers Prepared Under Princeton University's Carbon Mitigation Initiative Presented Here

	Natural Gas	Coal & Residuals Gasification
CO_2 Venting	Almost all H_2 produced today	Refineries, chemicals, NH_3 production in China 2) "Conventional technology"
CO_2 Capture	1) FTR vs. ATR with CC	2) "Conventional technology" 3) Membrane reactors 4) Overview

Scope of Presentation

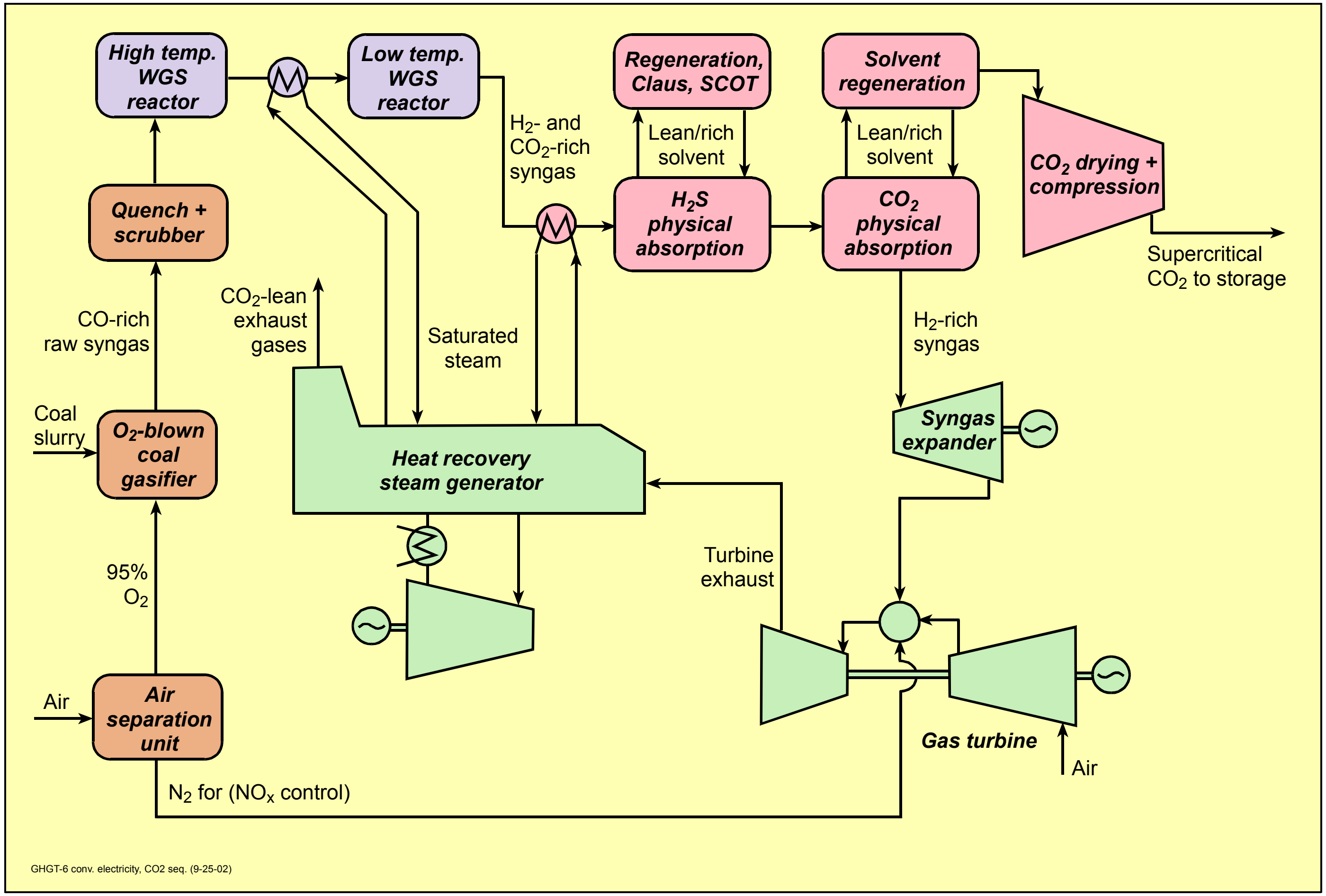
- Electricity from coal IGCC
- H_2 + electricity coproduct from coal
  - Conventional technology (like coal IGCC)
  - H_2 separation membrane reactor
- H_2 + electricity coproduct from natural gas
  - Fired tubular reactors (FTRs) (a.k.a. steam reformers)
  - O_2–blown autothermal reactors (ATRs)
- Effects of gasifier pressure on H_2 production from coal
- Gasifiers with synthesis gas coolers (syncoolers) vs. quench…comparing efficiencies and costs
- Cooled vs. uncooled turbines for H_2 separation membrane reactors
- Coal/natural gas competition in climate-constrained world
- CO_2 storage demo roles for gasification-based H_2 while awaiting the H_2 economy
- Outlook for electricity and H_2 via coal gasification in climate-constrained world

WHY COAL?

- Coal resources abundant globally
- Much of global population (*e.g., China, India*) heavily coal-dependent
- Coal prices low and not volatile
- Gasification:
  - near-zero emissions of air pollutants/GHGs
  - Potentially very attractive costs for coal-derived H_2 with CO_2 capture/storage
- Residual environmental, health, safety problems of coal mining

Benchmark: Coal IGCC Electricity with CO_2 Capture

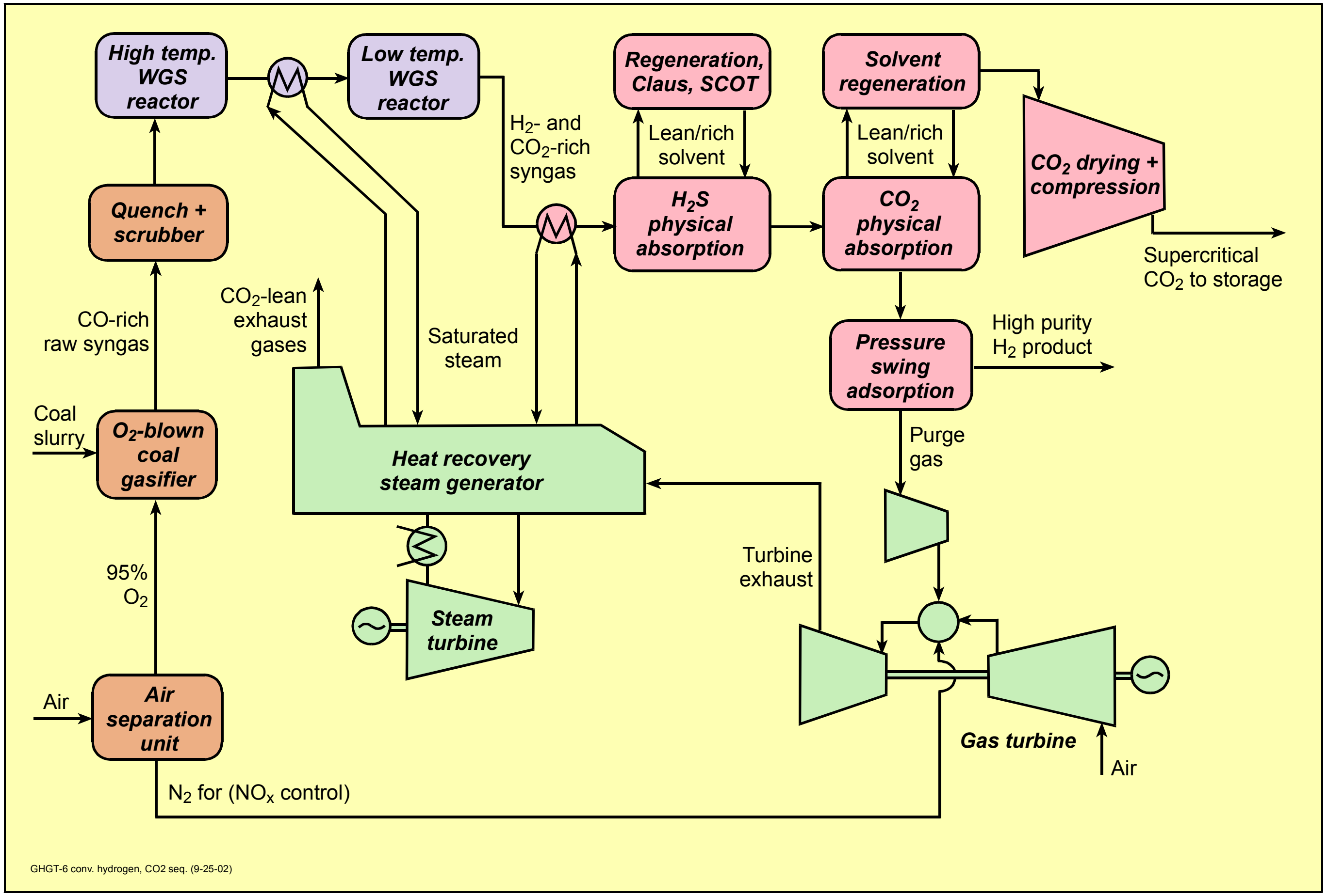
(70 bar gasifier)



- 362 MW_e [η = 34.9% (HHV)] @ $1807/$kW_e$ and 6.4¢/kWh [includes $5/t CO_2 (0.4¢/kWh) for CO_2 transport and underground aquifer storage]
- 390 MW_e (η = 40.8%) @ $1394/$kW_e$ and 4.7 ¢/kWh if CO_2 vented

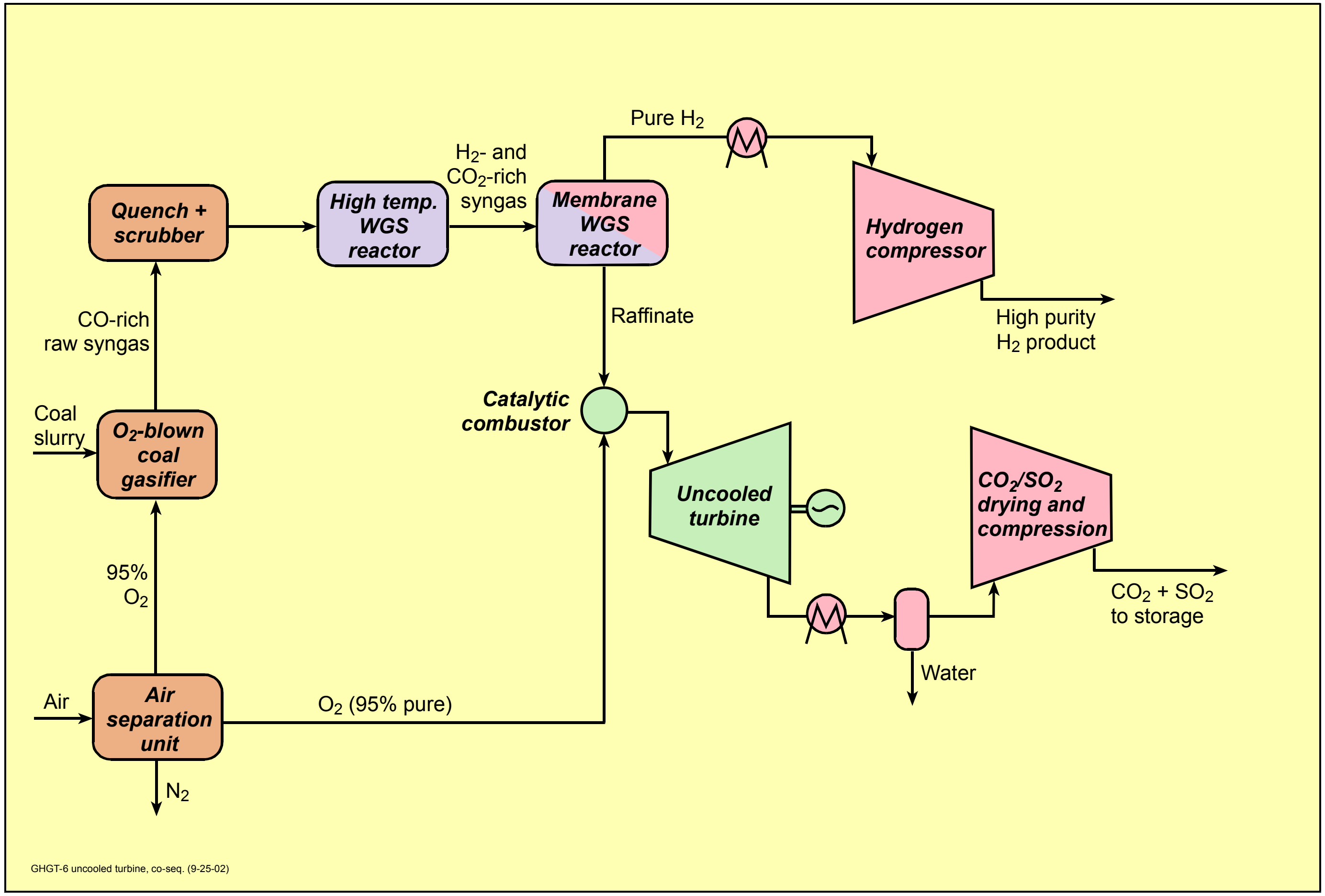
H_2 Production from Coal with CO_2 Capture

(70 bar gasifier)



- 1265 MW_h H_2 [η = 67.0% (HHV)] @ \$7.3/GJ [includes \$5/t CO_2 (\$0.6/GJ) for CO_2 transport and underground aquifer storage] + 39 MW_e electricity coproduct
- 1265 MW_h H_2 (η = 69.7%) @ \$6.2/GJ + 78 MW_e electricity coproduct w/CO_2 vented

H_2 Separation Membrane Reactor System (70 bar gasifier)



- Employ a H_2 permeable, thin film (10 μm), 60/40 % Pd/Cu (sulfur tolerant) dense metallic membrane, configured as a WGS membrane reactor
- . 1000 MW_h H_2 (η = 69.1%) @ $6.7/GJ [includes includes $5/t CO_2 ($0.7/GJ) for CO_2 transport and underground aquifer storage] + 18 MW_e electricity coproduct—assuming co-storage of SO_2 and CO_2

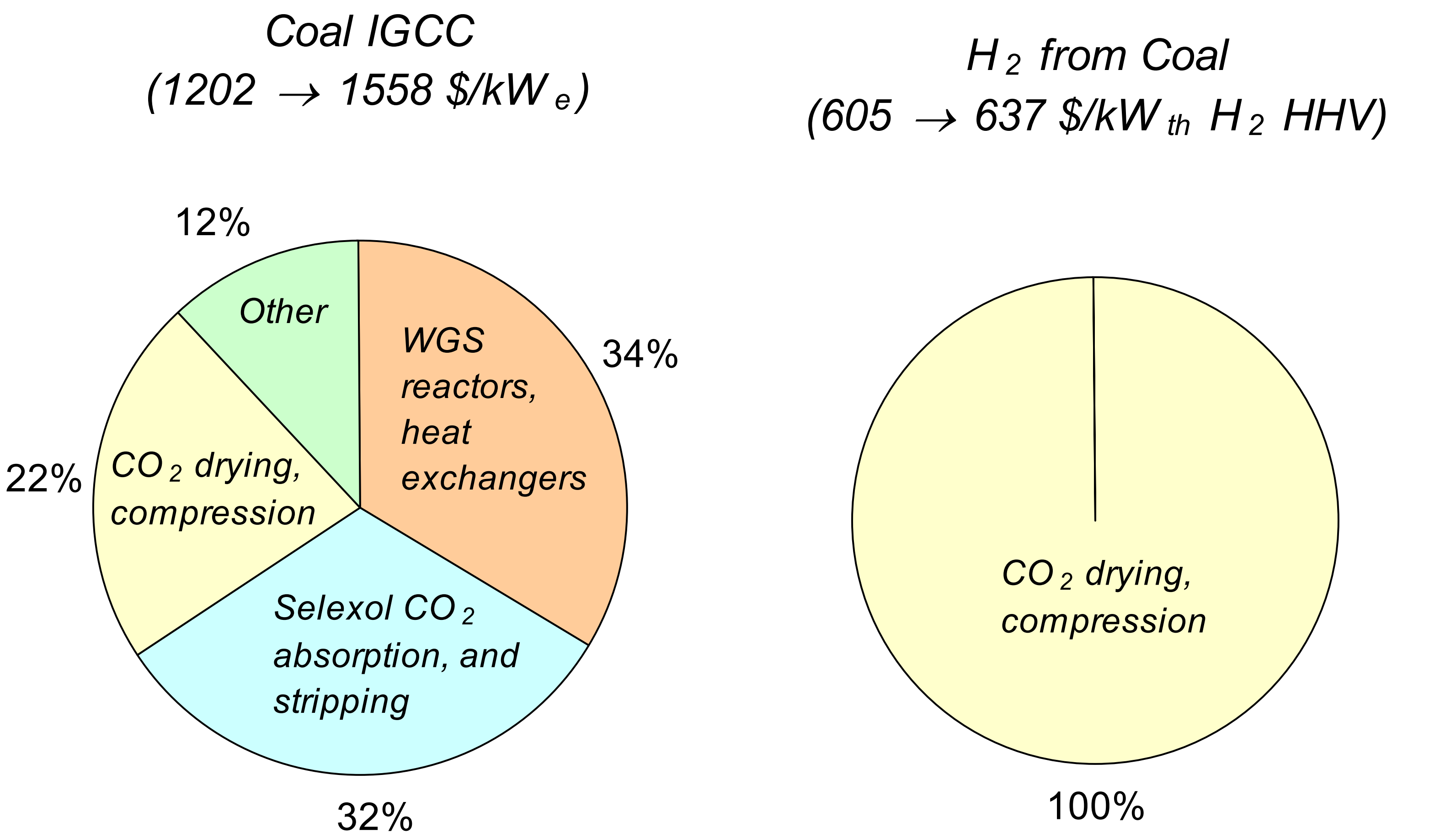
Electricity and H_2 Costs for Coal with CO_2 Capture + Storage

(*70 bar Gasifier, Conventional Technology*)

	CO_2 vented	CO_2 captured and stored	
Electricity only			
Output	390 MW_e	362 MW_e	-
Electricity Cost	4.7 ¢/kWh	6.4 ¢/kWh	-
Avoided cost (for capture only)	-	\$24 (\$18)/t CO_2	-
H_2 + electricity coproduction systems			
H_2 output (HHV)	1265 MW_h	1265 MW_h	268 MW_h
Electricity output	78 MW_e	39 MW_e	349 MW_e
Electricity value	4.7 ¢/kWh	6.4 ¢/kWh	6.4 ¢/kWh
H_2 cost (HHV)	\$6.2/GJ	\$7.3/GJ	\$5.5/GJ
Avoided cost (for capture only)	-	\$12 (\$6)/t CO_2	\$15 (\$9)/t CO_2

- No thermodynamic advantage to coproducing H_2/electricity (*unlike CHP*)
- Making large amounts of coproduct electricity is worthwhile only for high electricity prices
- Coproduction with power output ~ stand-alone power plants + modest H_2 output ➔ H_2 cost with CO_2 capture/storage < for plants producing mainly H_2 with CO_2 vented if electricity value = electricity cost for stand-alone IGCC with CO_2 capture/storage

Breakdown of Incremental Capital Cost for CO_2 Capture



- Incremental cost for CO_2 capture is less for hydrogen than electricity because much of the equipment is already needed for a H_2 plant.

Electricity and H_2 Coproduction for Natural Gas

- CMI modeling of H_2 from NG embryonic
- Initial focus on thermodynamic modeling of
  - Fired tubular reformers (FTRs)—i.e., steam reformers (@ *25 bar, 850 ^oC*)
  - Oxygen-blown autothermal reactors (ATRs) (@ *70 bar, 950 ^oC*)
- Industrial interest in H_2 for chemical/refining industry needs usually focused on systems that produce zero net electricity (*just enough to meet onsite needs*)
- If H_2 is produced at large scales for energy in climate-constrained world, coproduction of electricity via combined cycles might sometimes be considered:
  - Electricity manufacture from some of produced H_2 can sometimes lead to high marginal efficiencies ($\eta > 80\%$) in converting H_2 to electricity
    - For FTR + CC coproduction carbon removal rates are not higher than ~ 50%
    - For ATRs operated with steam/carbon ratios ≥ 1.5, carbon removal rates higher than 80% can be realized
  - Whether such opportunities can be cost justified remains to be determined
-

CO_2 Storage vs Co-Storage of CO_2 and H_2S or SO_2

(*70 bar coal gasifier with quench*)

	CO_2 vented	S recovery, CO_2 stor	CO_2 + H_2S co-stor
Elect gen cost, conv tech	4.7 ¢/kWh	6.4 ¢/kWh	6.0 ¢/kWh
Avoided cost (*capture only*)	-	\$24 (\$18)/t CO_2	\$18 (\$13)/t CO_2
H_2 prod cost, conv tech	\$6.2/GJ	\$7.3/GJ	\$6.7/GJ
Avoided cost (*capture only*)	-	\$12 (\$6)/t CO_2	\$6 (\$0.5)/t CO_2
		FGD, CO_2 stor	CO_2 + SO_2 co-stor
H_2 prod cost, Pd/Cu membrane		\$7.2/GJ	\$6.7/GJ
Avoided cost (*capture only*)		\$10 (\$4)/t CO_2	\$5 (- \$0.4)/t CO_2

- Carbon-Sulfur co-capture/co-storage leads to lower costs, mainly due to reduced capital requirements—avoided cost for capture is near zero
- Potential risks of co-storage options should be studied to determine feasibility of these options

Effect of Coal Gasifier Pressure on H_2 Cost (*\$/GJ, HHV*) with CO_2 Co-Capture/Co-Storage

	70 bar	120 bar
Conventional technology	\$6.7/GJ ($1265\ MW_h + 39\ MW_e$)	\$6.6/GJ ($1244\ MW_h + 51\ MW_e$)
Pd/Cu membrane technology	\$6.7/GJ ($1000\ MW_h + 18\ MW_e$)	\$6.2/GJ ($1000\ MW_h + 56\ MW_e$)

- 70 bar desirable w/conv tech…obviates H_2 compression for pipeline transport…but only marginal potential incremental benefits at 120 bar
- Higher pressures seem promising for dense metal membrane systems
- Microporous membrane systems might benefit even more:

H_2 flux ratio, microporous membrane/dense metal membrane

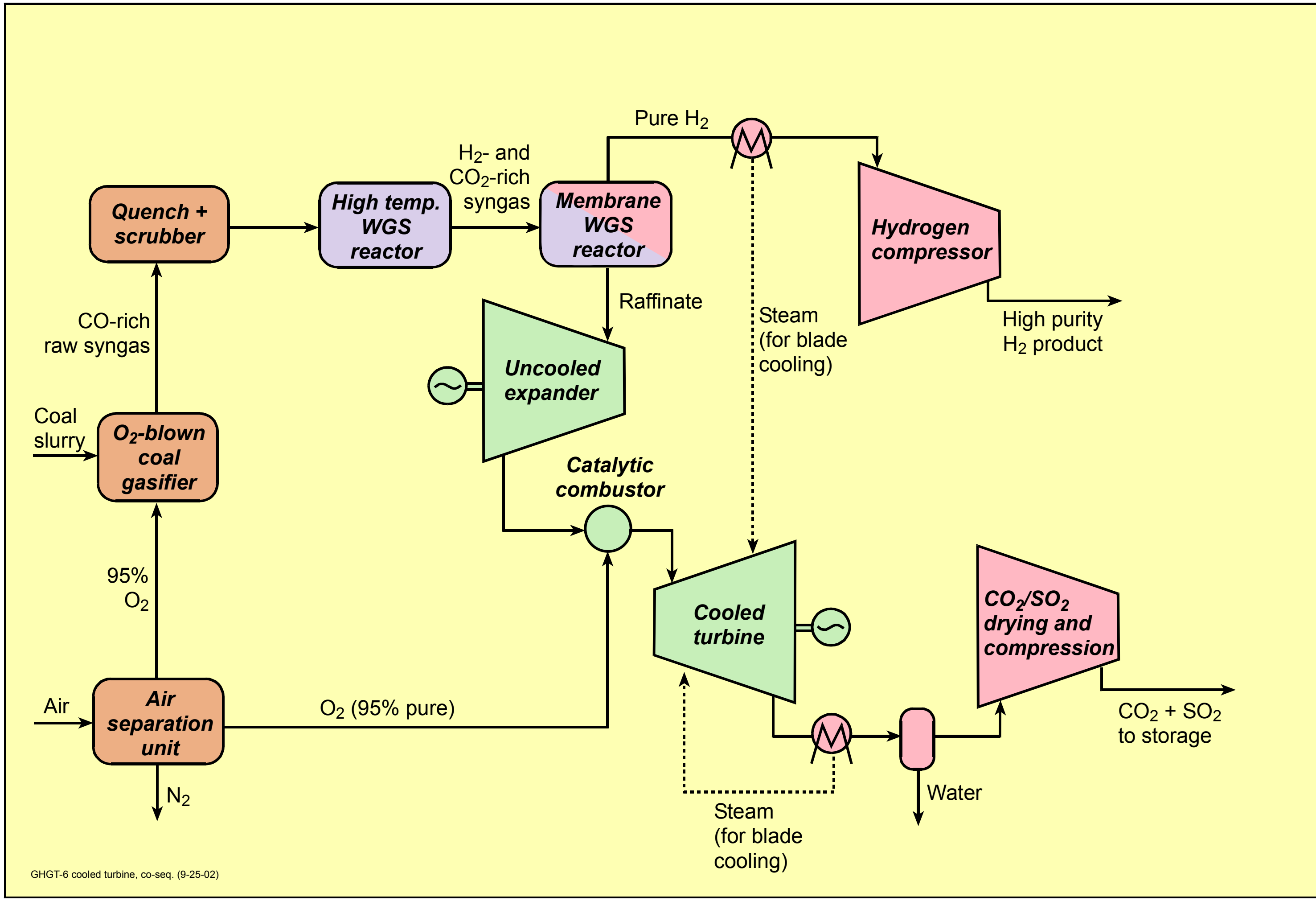
$$\sim [(P_{h1} - P_{h2})/(P_{h1}^{0.5} - P_{h2}^{0.5})] = (P_{h1}^{0.5} + P_{h2}^{0.5})$$

Improving Efficiency, 70 bar Coal Gasifiers, Conv. Tech.

	Efficiency (HHV) for CO_2		Cost for CO_2	
	Vented	Cap/Stor	Vented	Cap/Stor
Electricity	η_e = 100*(elect out)/(coal in)		(*in ¢/kWh*)	
Quench	40.8	34.9	4.7	6.4
Syncooler	44.3	37.1	5.1	6.9
H_2	η_h = 100*(H_2 out)/[coal in – (elect out/η_e)]		(*in $/GJ, HHV*)	
Quench	69.7	67.0	6.2	7.3
Syncooler	72.9	69.6	7.0	8.3

- Efficiency improvement strategies for coal sometimes important (*e.g., cooled turbine for H_2 via membranes when electricity coproduct value high—will show*)
- But efficiency gains often not cost-effective (*coal prices low*)
- Syncoolers make less sense relative to quench for H_2 than for electricity …though syncoolers for H_2 separation via membrane reactors merit attention
- For energy systems with CO_2 capture/storage, efficiency important only to extent that costs are reduced in climate-constrained world

Membrane System with Cooled Raffinate Turbine



- Blade cooling enables higher TIT (1250 °C vs. 850 °C) and higher electrical conversion efficiency for raffinate stream. Requires much lower H_2 recovery factor (~60%) than for uncooled turbine (~ 85% H_2 recovery factor)…can be worthwhile if electricity value high

Cooled vs. Uncooled Turbine for H_2 Manufacture (*Pd/Cu membrane*) @ 1 GW_h, 120 bar Gasifier, Syngas Expander

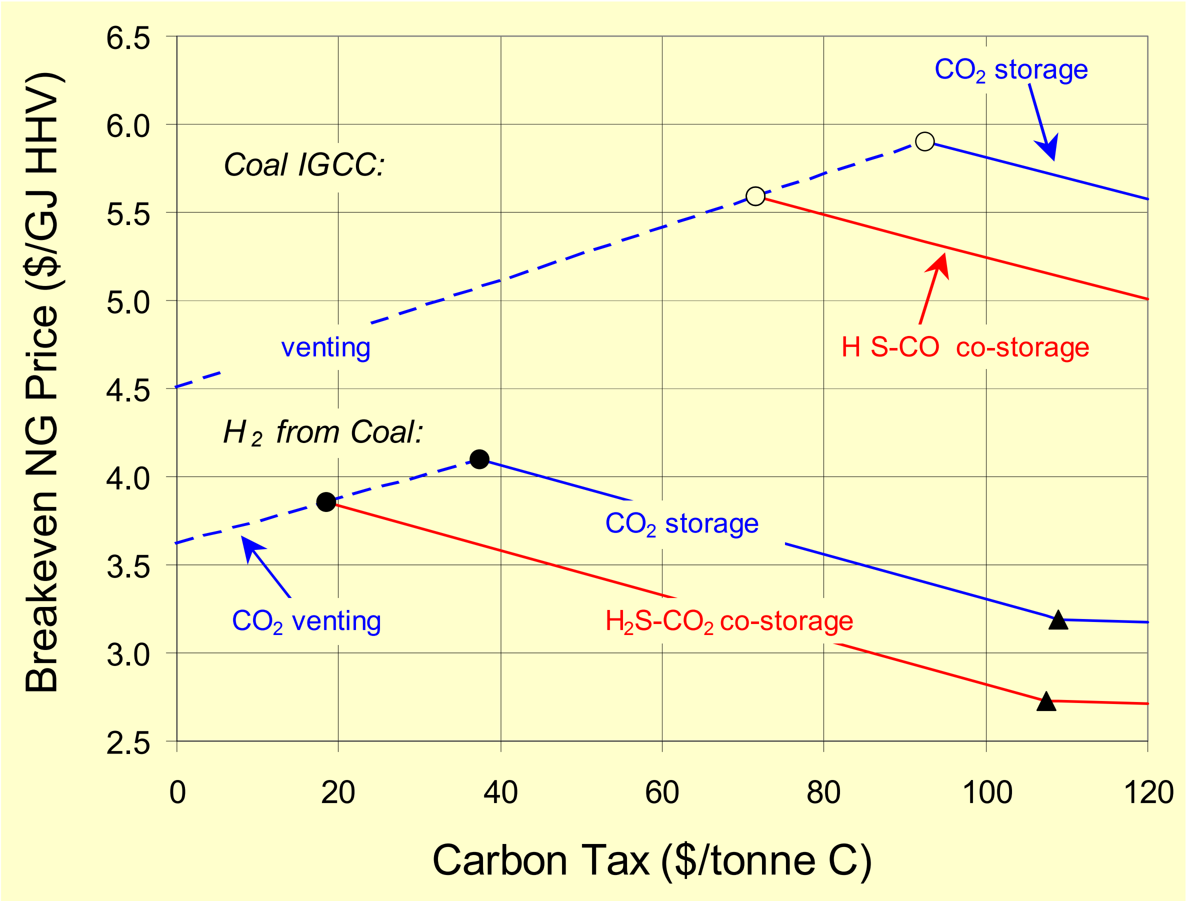
Turbine type	Electricity Coproduct	TIT	Cost of H_2 (*\$/GJ*) with CO_2 capture/storage for electricity @:	
			6.0 ¢/kWh	3.0 ¢/kWh
Uncooled	55 MW_e	850 ^oC	\$6.1/GJ	\$6.6/GJ
Cooled	304 MW_e	1250 ^oC	\$4.8/GJ	\$7.3/GJ

Turbine cooling worthwhile if electricity prices are high
…e.g., if, under climate constraint, electricity is valued at cost for decarbonized coal IGCC

Summarizing Outlook for Membrane Reactors

- Co-capture and co-storage of SO_2 and CO_2 would probably be cost-effective…though viability of co-storage option requires clarification
- Increasing gasifier pressure (*70 → 120 bar*) raises system efficiency and offers potentially lower H_2 cost…if electricity coproduct has high value
- Using gasifiers with quench, potential cost reduction relative to "conventional technology":
  - ~ 10% for dense metal (Pd/Cu) membranes
  - ~ 20% for microporous ceramic membranes (*but H_2 purity issues*)
  - Not larger potential savings because gas separation not large fraction of capital cost
- For future study:
  - microporous membranes with syncoolers and lower steam-to-carbon ratio
  - ion-transport membrane for O_2 production

Coal/NG Competition in Electricity & H_2 Manufacture (for coal @$1.2/GJ)



- NGCC for NG electricity (*based on EPRI/DOE*); FTR for NG H_2 (*based on FW*)
- H_2 from coal with CO_2 cap/stor competitive with H_2 from NG with CO_2 vented at much lower NG prices than for electricity
- Much lower carbon taxes needed to induce CO_2 cap/stor for coal than for NG.

WHILE WAITING FOR A H_2 ECONOMY

- H_2 won't be widely used as energy carrier for at least 20-30 years
- But H_2 use in chemical/refining industries ~ 1% of global energy
- Gasification-based H_2 production at refineries/tar sands conversion plants (*via gasification of coke, pitch*) and NH_3 plants might be exploited as low-cost source of CO_2 for "megascale demonstration projects" of CO_2 storage in various geological media
  - Offering plant-gate CO_2 costs $\leq$ \$6/t (~ *\$0.3/Mscf*) gasification-based H_2 production plants often competitive even with natural CO_2 supplies for EOR projects
  - Are suitable CO_2 storage demo sites near prospective industrial H_2 production sites?
- Such demo projects might be considered for China as well as for industrialized countries in light of China's deep involvement with NH_3 production via gasification [China produces 5 million t/y of H_2 (*98% at NH_3 plants*) out of 40 million t/y worldwide]

Plant-Gate CO_2 Costs with CO_2 Capture

Plant type	Plant output	CO_2 disposal rate (t/h)	Plant-gate CO_2 cost ($/t)
NGCC (store) (*from EPRI*)	311 MW_e	118	58
Coal UCS (store) (*from EPRI*)	367 MW_e	335	33
NG H_2 (store) (*from FW*)	1000 MW_h	204	24
IGCC (store)	362 MW_e	301	15.6
IGCC (co-store)	362 MW_e	301	10.6
Coal H_2 (store), conv tech	1265 MW_h	554	6.1
Coal H_2 (store), Pd/Cu memb.	1000 MW_h	486	3.0
Coal H_2 (co-store), conv tech	1265 MW_h	554	0.5
Coal H_2 (co-store), Pd/Cu memb.	1000 MW_h	496	- 0.4

Costs for CO_2 coproduct of H_2 produced at refineries via petroleum residuals gasification would be similar to those for coal systems.

Outlook for Fossil Fuel Competition in Power Markets in Climate-Constrained World

- IGCC favored technology for *new* coal power plants in climate-constrained world
- For IGCC, worthwhile to capture/store carbon @ CT ~ \$100/tC << than required to decarbonize NGCC
- Still, primary energy and generation cost penalties are significant for coal IGCC w/capture/storage (~ *16% and 35%, respectively*)
- Not urgent to decarbonize new NGCC plants (*w/venting, emissions < ½ for IGCC*)
- At CT ~ \$100/tC, IGCC +CO_2 cap/stor cannot compete with NGCC + CO_2 venting—until P_{NG} ➔ \$6/GJ…or major IGCC capital cost reductions are realized
- Severe climate policy constraint ➔ shift to NG at expense of coal for power➔ potential loss of coal energy infrastructure ➔ deleterious long-term impact because of coal's promise in serving H_2 markets

Outlook for Fossil Fuel Competition in Making H_2 in Climate-Constrained World

- As for electricity, needed $(CT)_{coal\ H2} << (CT)_{NG\ H2}$ for inducing CO_2 capture/storage
- Primary energy and production cost penalties for capture/storage are much lower than for for coal IGCC (*~ 4% and 19%, respectively*)
- Unlike electricity, good prospects that coal H_2 w/capture/storage competitive with NG H_2 w/venting for P_{NG} ~ $4.0/GJ
- Making H_2 for energy is outstanding (*long-term*) opportunity for coal
- Transition to coal H_2 difficult because of market threat to coal power industry from NG in early years of transition to low C energy economy