

Production of Hydrogen and Electricity from Coal with CO₂ Capture

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Princeton University

Carbon Mitigation Initiative (CMI)

CMI Carbon Capture Group:

- Investigating the H₂/Electricity Economy

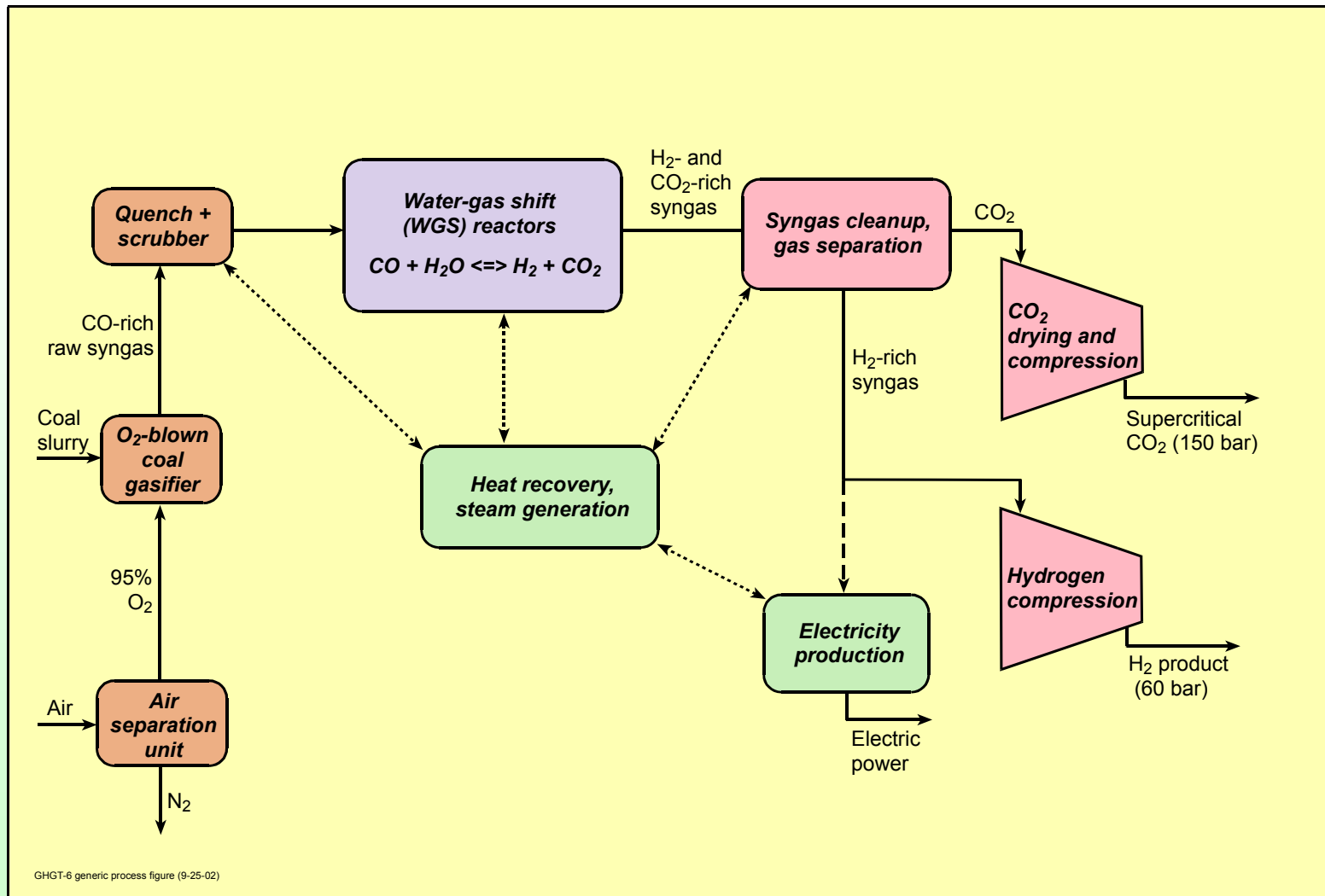
Activities:

- H₂/electricity production from fossil fuels
- H₂ (and CO₂) distribution
- H₂ utilization (e.g. fuel cells, combustion)
- Princeton/Tsinghua collaboration on low emission energy technologies for China

Background and Motivation

- Distributed energy use (transportation and heating) responsible for ~2/3 of global CO₂ emissions
- CO₂ capture, compression, dehydration, and pipeline transport from distributed sources is *very* expensive.
- Low carbon energy carriers are needed: electricity and hydrogen.
- If CO₂ sequestration is viable, fossil fuel decarbonization likely to be the cheapest route to electricity and hydrogen for many decades.
- Coal is of great interest because it is:
 - *Plentiful*. Resource ~ 500 years (vs. gas/oil: ~100 years).
 - *Inexpensive*. 1-1.5 \$/GJ HHV (vs. gas at 2.5+ \$/GJ).
 - *Ubiquitous*. Wide geographic distribution (vs. middle east).
 - *Clean?! Gasification, esp. with sequestration, produces little gaseous emissions and a chemically stable, vitreous ash.*
- *Example*: China: extensive coal resources; little oil and gas. Potential for huge emissions of both criteria pollutants and greenhouse gases.

Generic Process: Coal to H₂, Electricity, and CO₂

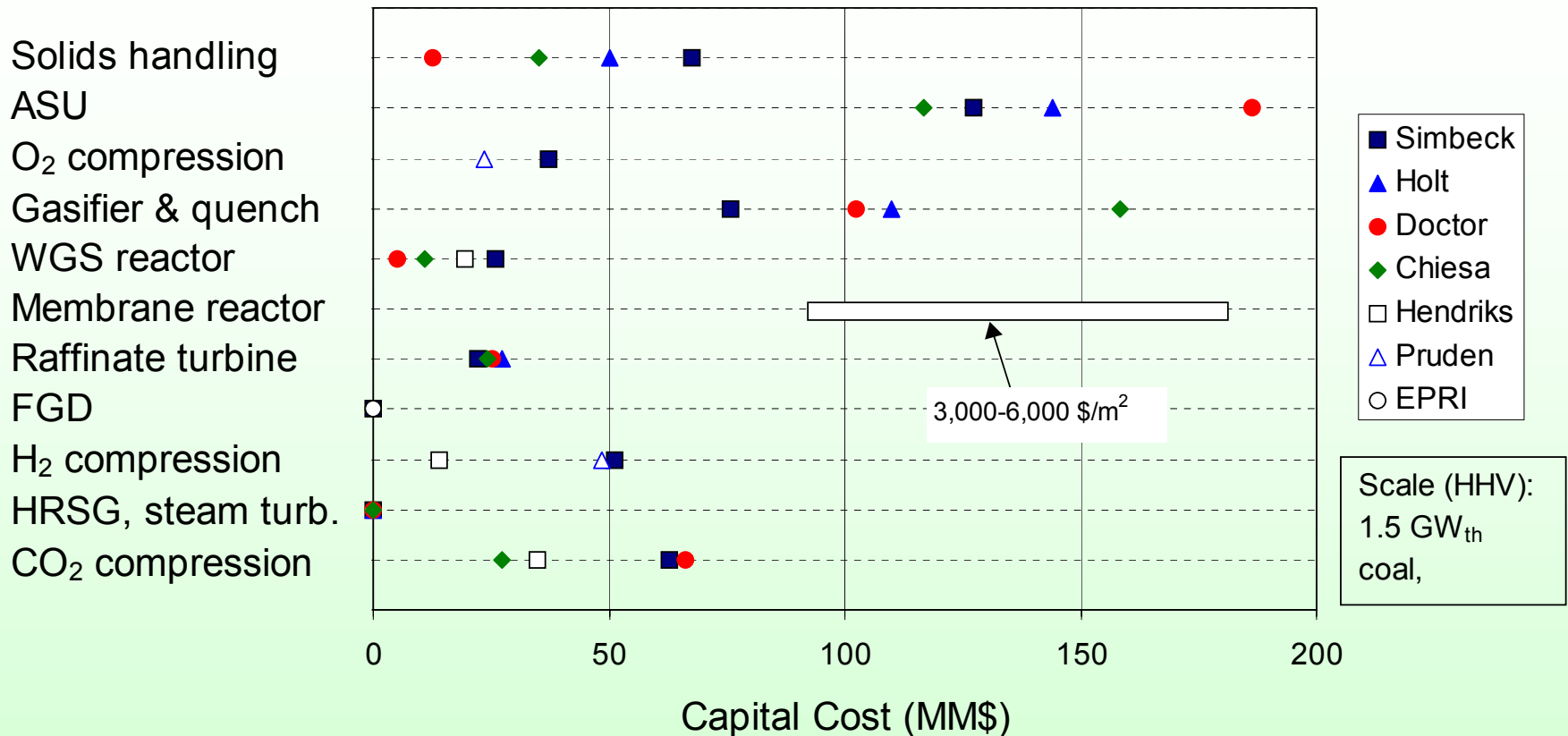


- All work presented here is based on O₂-blown, entrained flow, coal gasification (e.g. Texaco, E-Gas gasifiers).

Process Modeling

- Heat and mass balances (around each system component) calculated using:
 - Aspen Plus (commercial software), and
 - GS (“Gas-Steam”, Politecnico di Milano)
- Membrane reactor performance calculated via custom Fortran code
- Component capital cost estimates taken from the literature, esp. Holt, et al. and EPRI reports on IGCC
- Benchmarking/calibration:
 - Economics of IGCC with carbon capture studied by numerous groups
 - Used as a point of reference for performance and economics of our system
 - Many capital-intensive components are common between IGCC electricity and H₂ production systems (both conventional and membrane-based)

Estimates of Overnight Component Capital Costs



- Significant variation found in cost values, methodology, and depth of detail.
- Our cost model is a self-consistent set of values from the literature.
- Cost database is evolving; less reliable values removed; range is narrowing.
- Uncertainty shown above leads to an uncertainty of $\pm 10-15\%$ in H₂ cost.

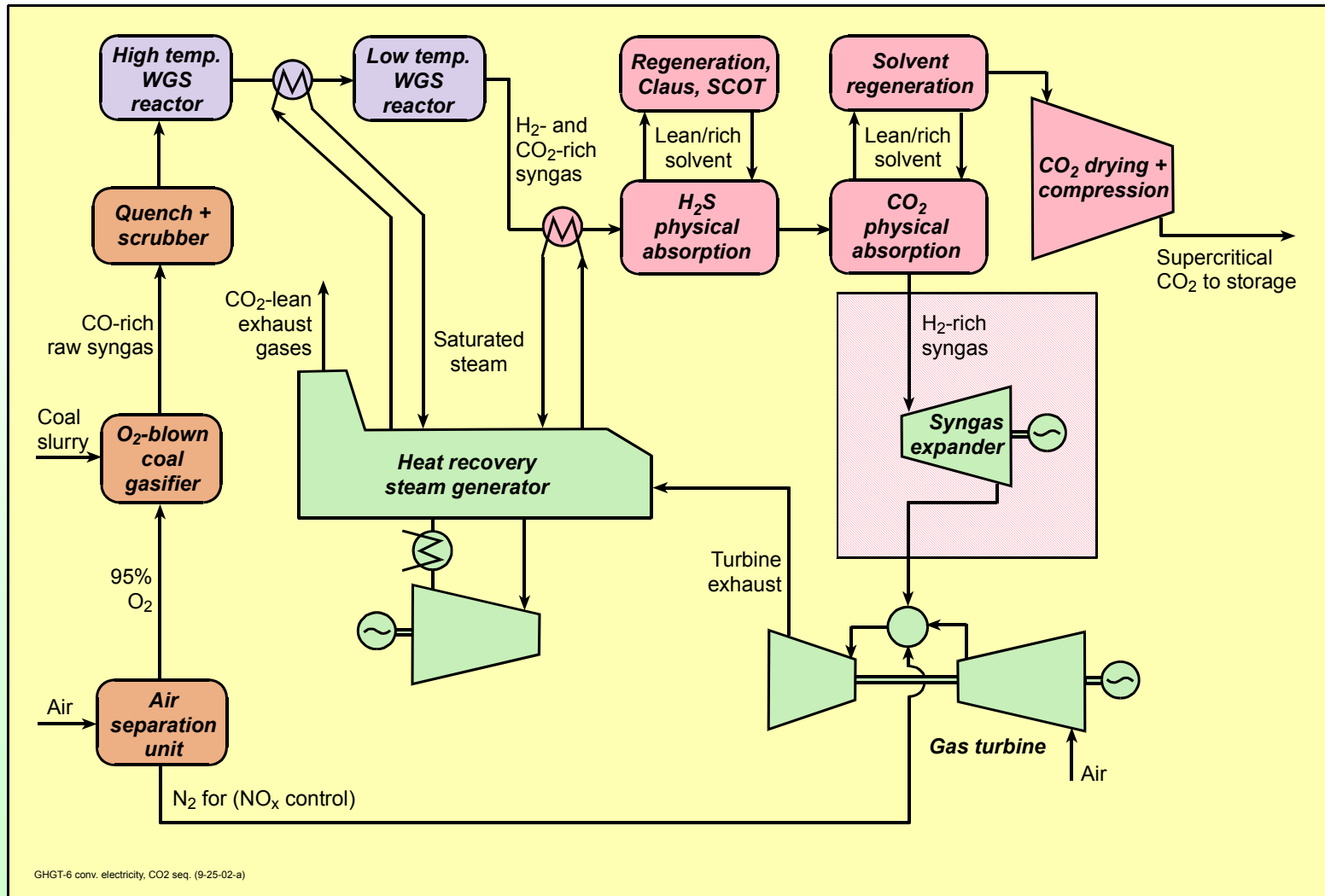
Economic Assumptions

Coal price (year 2020 EIA est.)	0.94 \$/GJ (HHV)
Capacity factor	80%
Capital charge rate	15% per yr
Balance of plant (BOP) costs	23% of gasifier island (GI) capital
Engineering fees (EF)	15% of (GI+BOP)
Process/project contingency	15% of (GI+BOP+EF)
Plant lifetime*	25 yr
Construction time*	4 yr
Interest during construction (IDC)	16.0% of overnight capital**
O&M costs	4% of overnight capital per year
CO ₂ sequestration cost	5 \$/mt CO ₂ (~0.5 \$/GJ H ₂ HHV)
U.S. dollars valued in year	2001
Plant scale	1 GW _{th} H ₂

* Used only in calculating the interest during construction and/or plant internal rate of return

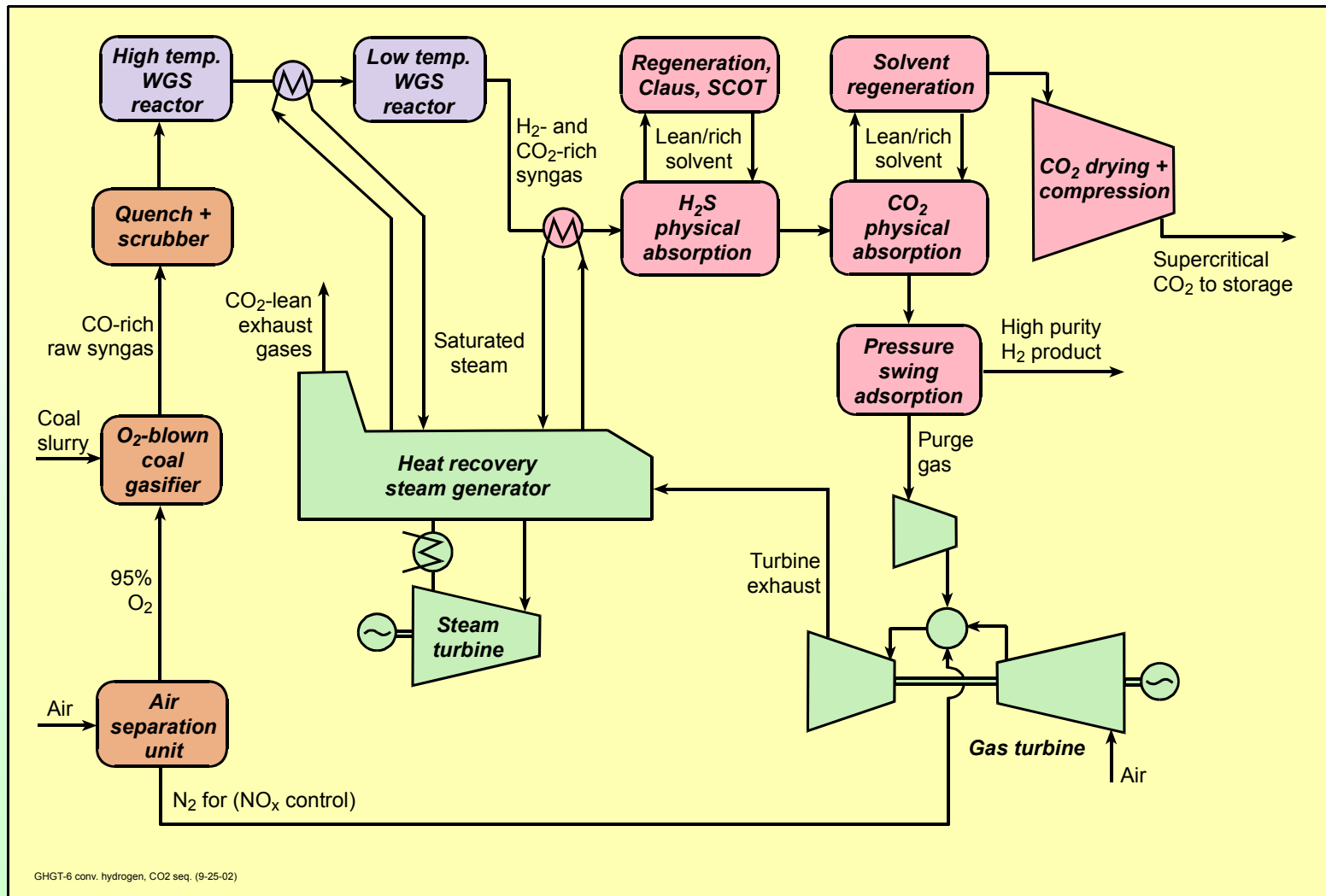
** Assuming a 10% real interest rate

H₂ Production: Add H₂ Purification/Separation



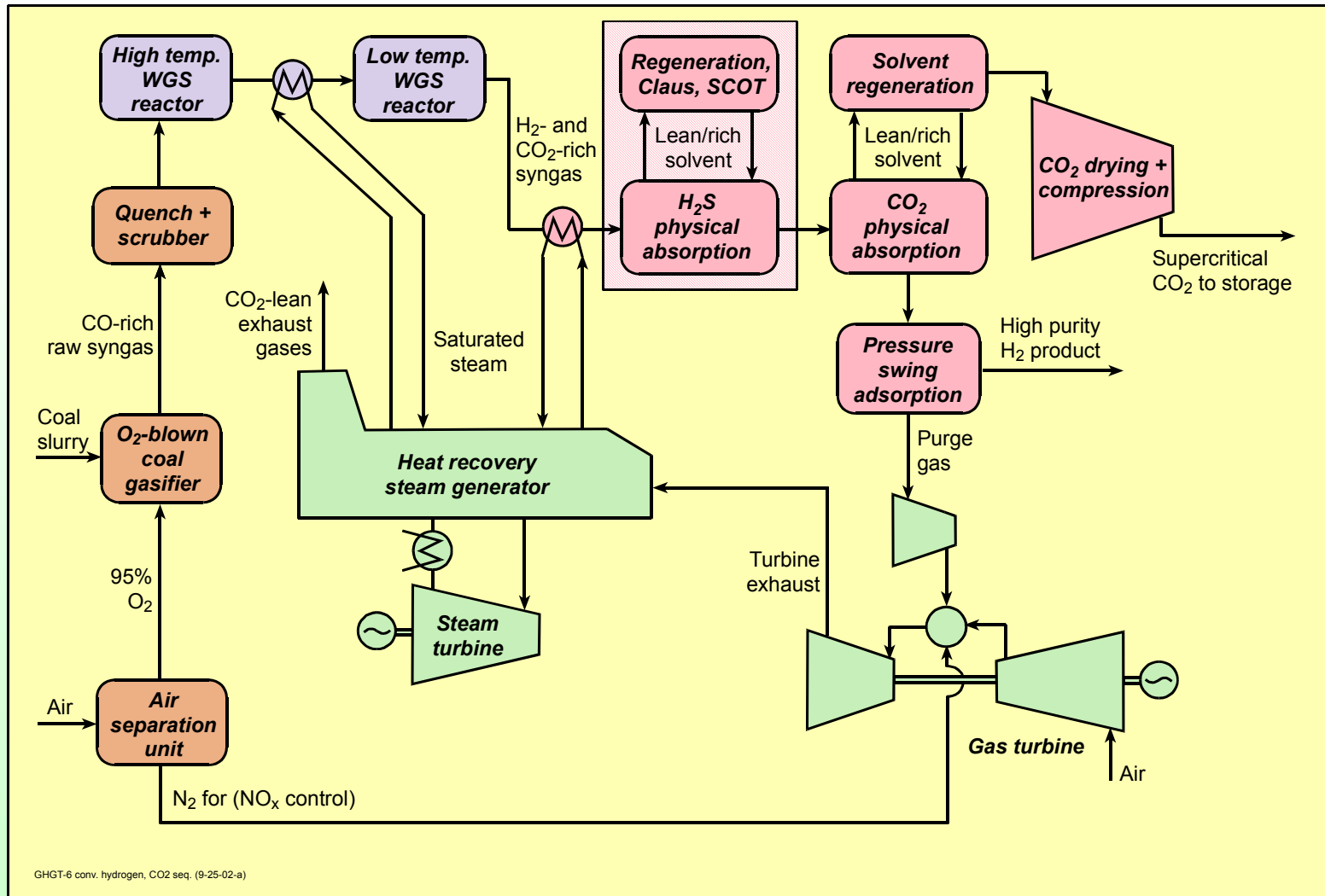
- Replace syngas expander with PSA and purge gas compressor.

Conventional H₂ Production with CO₂ Capture



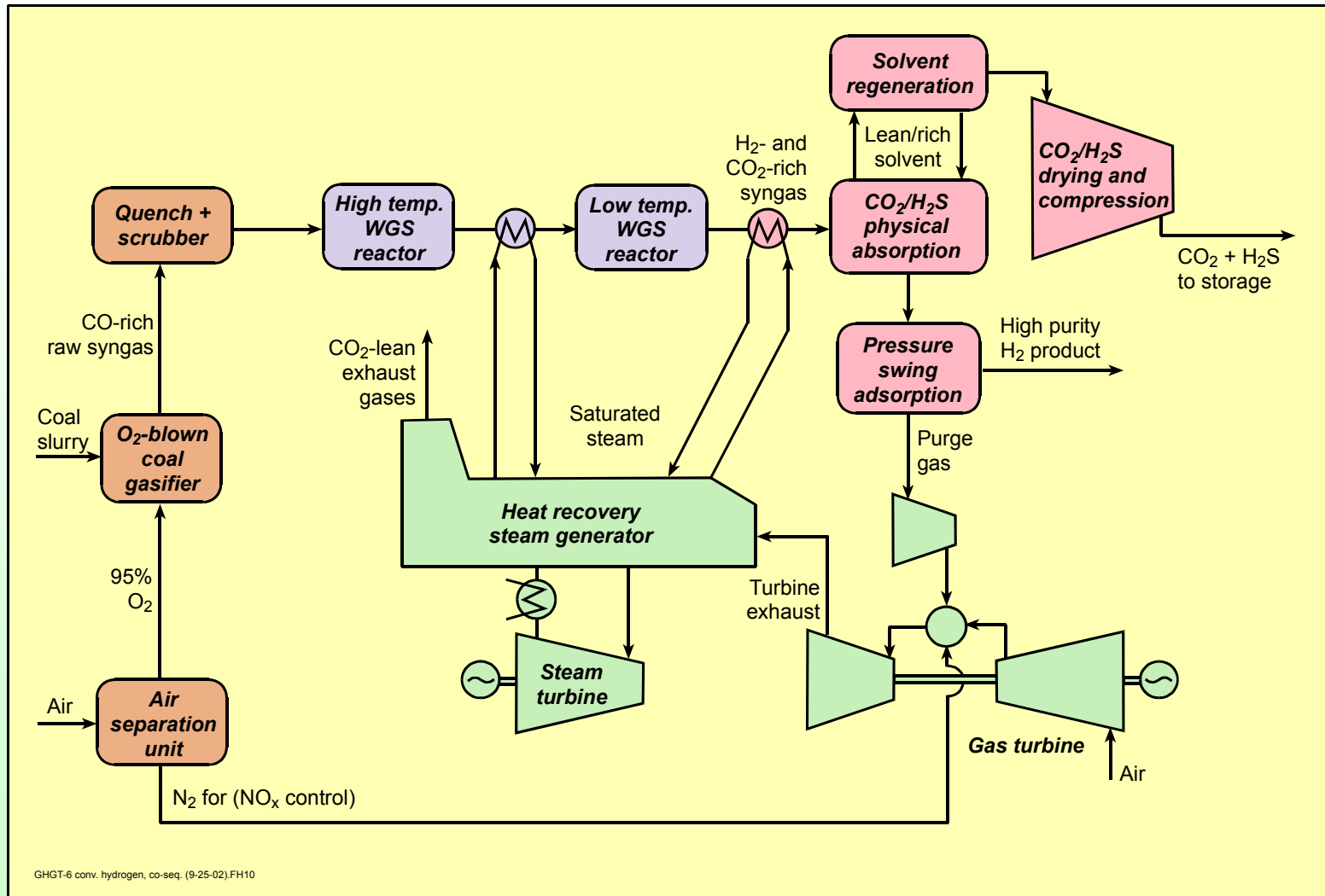
- H₂ cost: 7.1 \$/GJ (HHV). (85% HRF, scale: 1 GW_{th} H₂ HHV, 3.0 ¢/kWh)

Capture (and Co-sequester) H₂S with CO₂



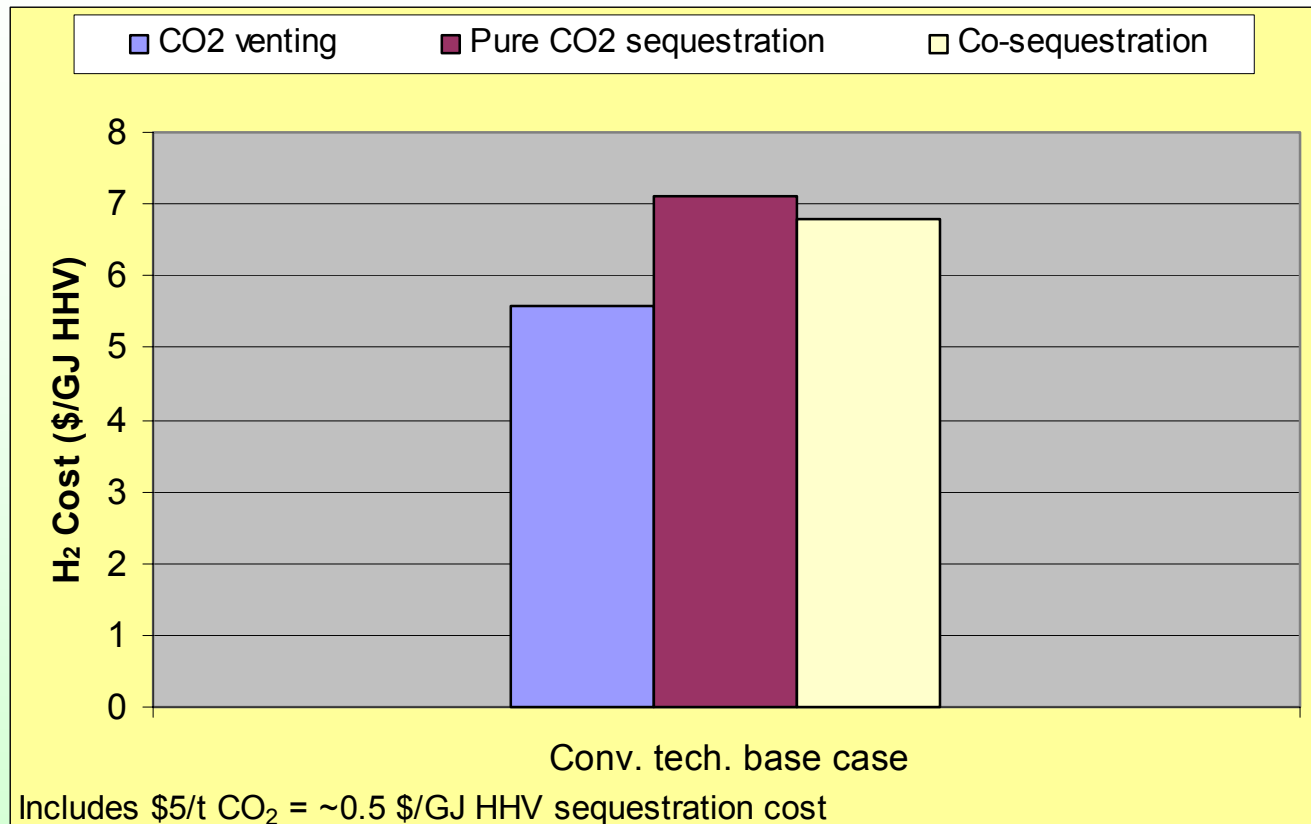
- Remove the traditional acid gas recovery (AGR) unit.

Conventional H_2 Production with CO_2/H_2S Capture



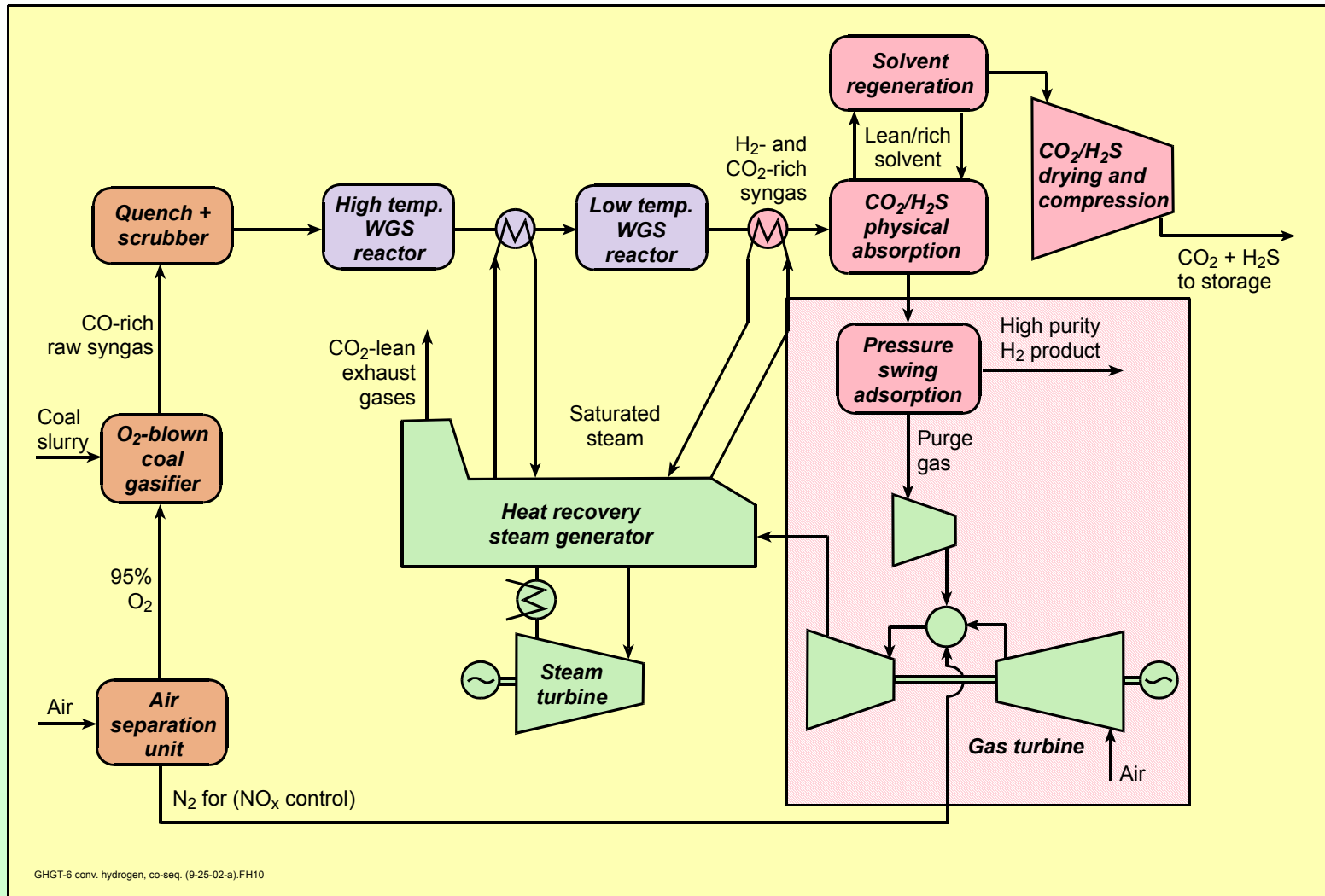
- Resulting system is simpler and cheaper.

Conventional H_2 with Co-Sequestration of CO_2 and Sulfur-bearing Species



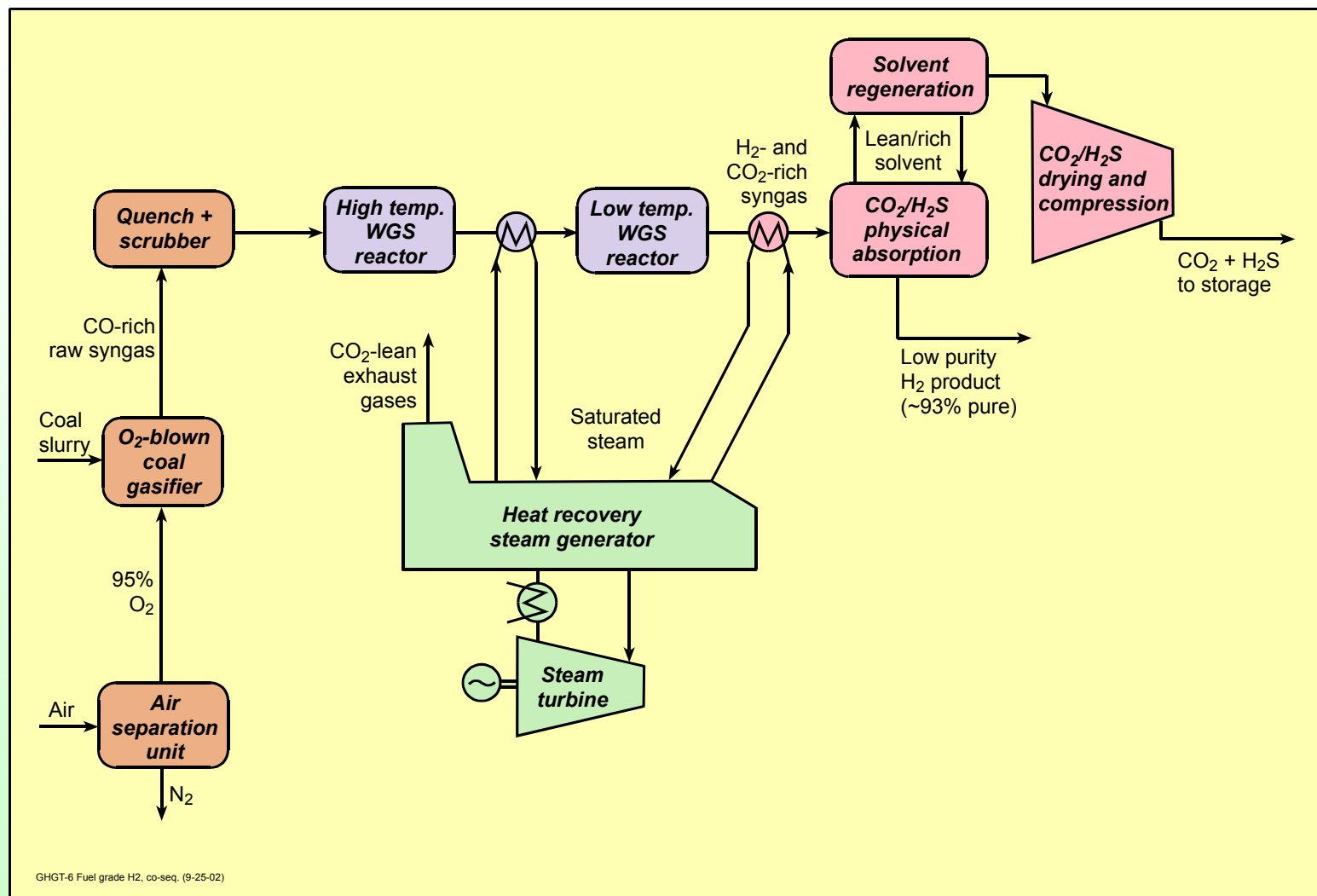
- **CO₂ capture and sequestration lowers efficiency by ~3% and increases H₂ cost by ~ 1.5 \$/GJ.**
(Cost of CO₂ pipeline transport and disposal used here is 0.4-0.6 \$/GJ.)
- **Co-sequestration has potential to lower H₂ cost by 0.25-0.75 \$/GJ, depending on sulfur content of coal.**

Produce “Fuel Grade” H_2 with CO_2/H_2S Capture



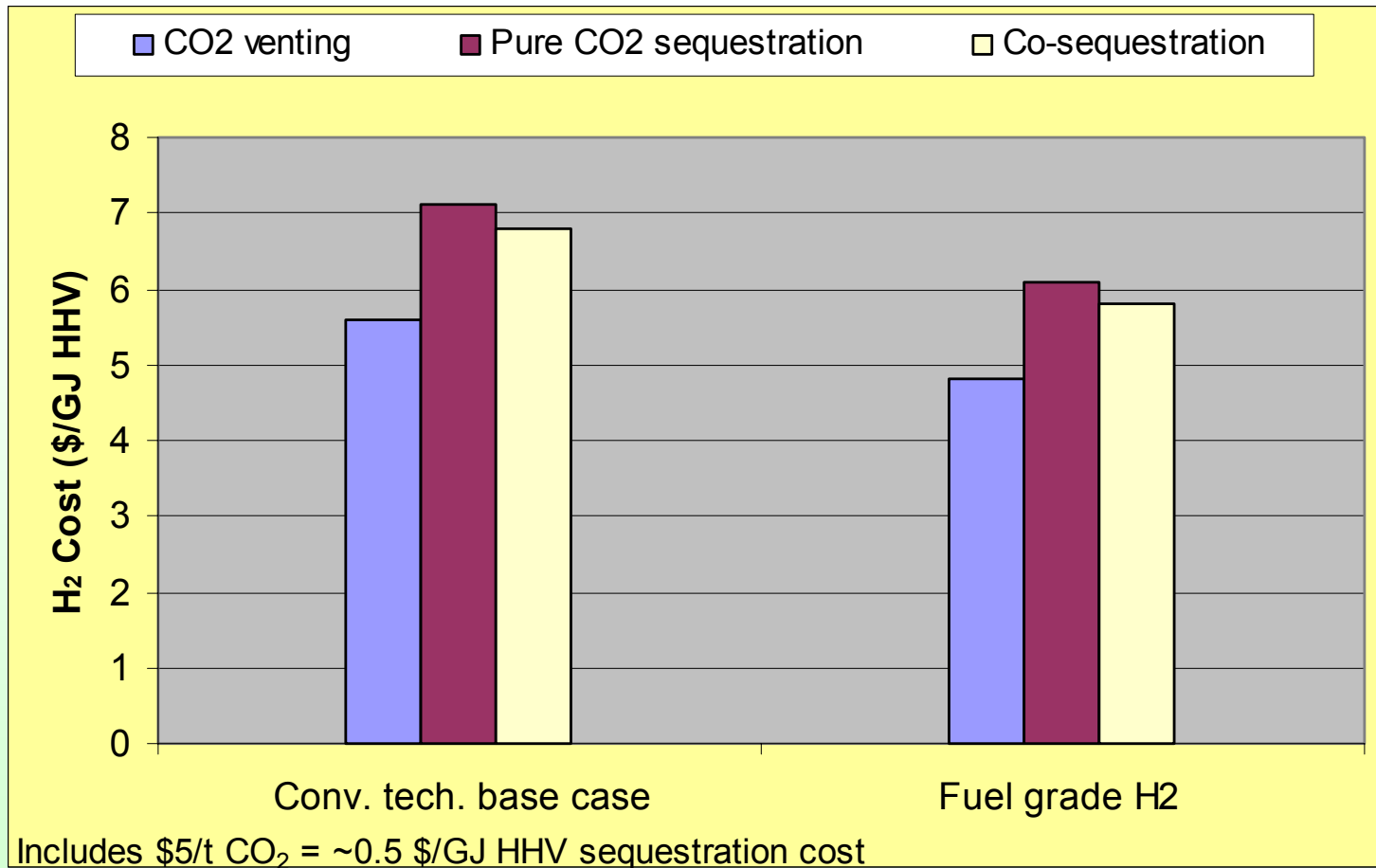
- Remove the PSA and gas turbine; smaller steam cycle.

“Fuel Grade” (~93% pure) H_2 with CO_2/H_2S Capture



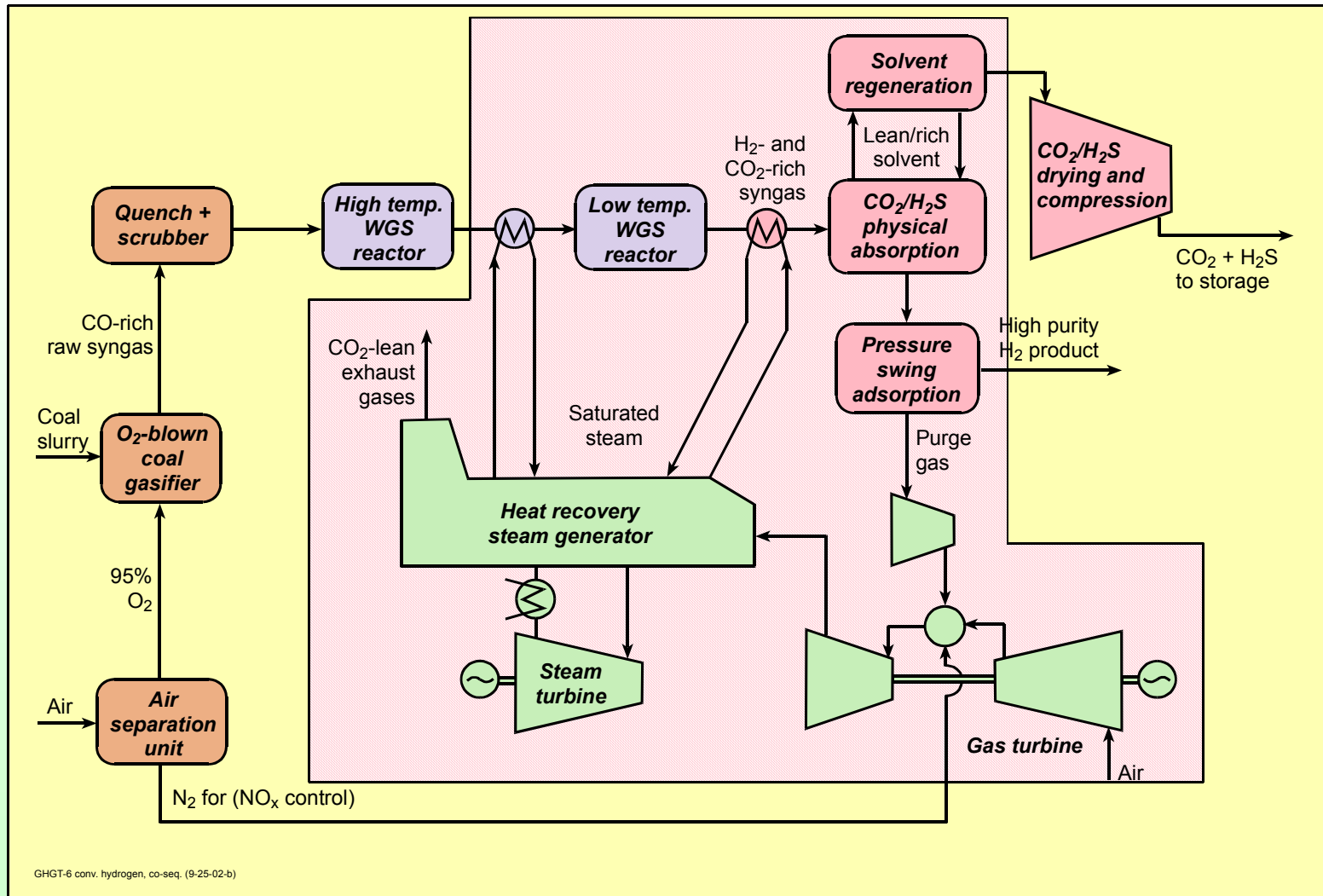
- Simpler, less expensive plant. No novel technology needed.

Production of "Fuel Grade" H₂



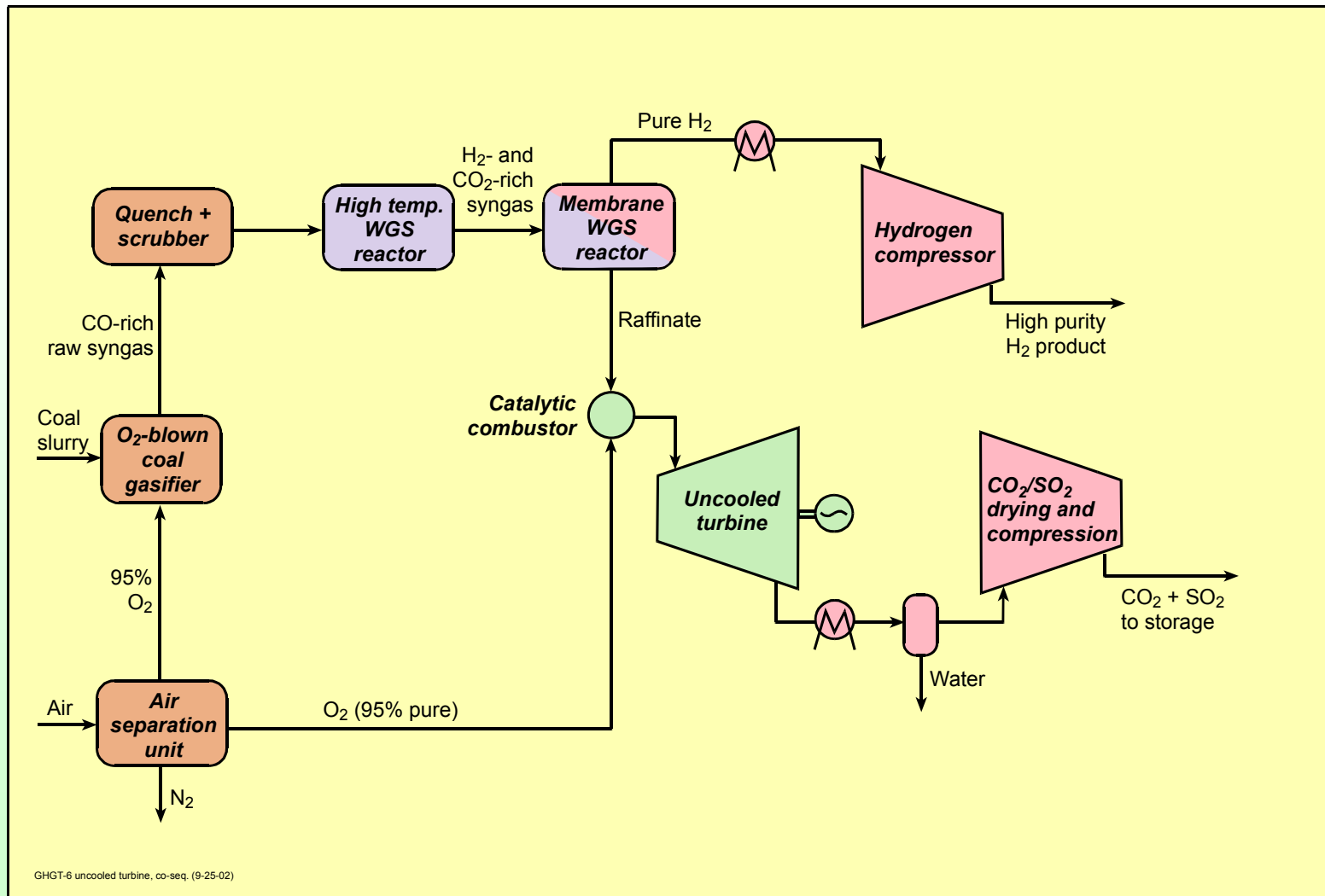
- Reduced H₂ purity yields a significant cost savings: 1.0-1.4 \$/GJ.
- Fuel grade H₂ will be more competitive with gas and oil in the heating sector, and might be adequate for transportation (H₂ ICEVs; barrier to PEM FCEVs?)

Change H_2 - CO_2 Gas Separation Scheme



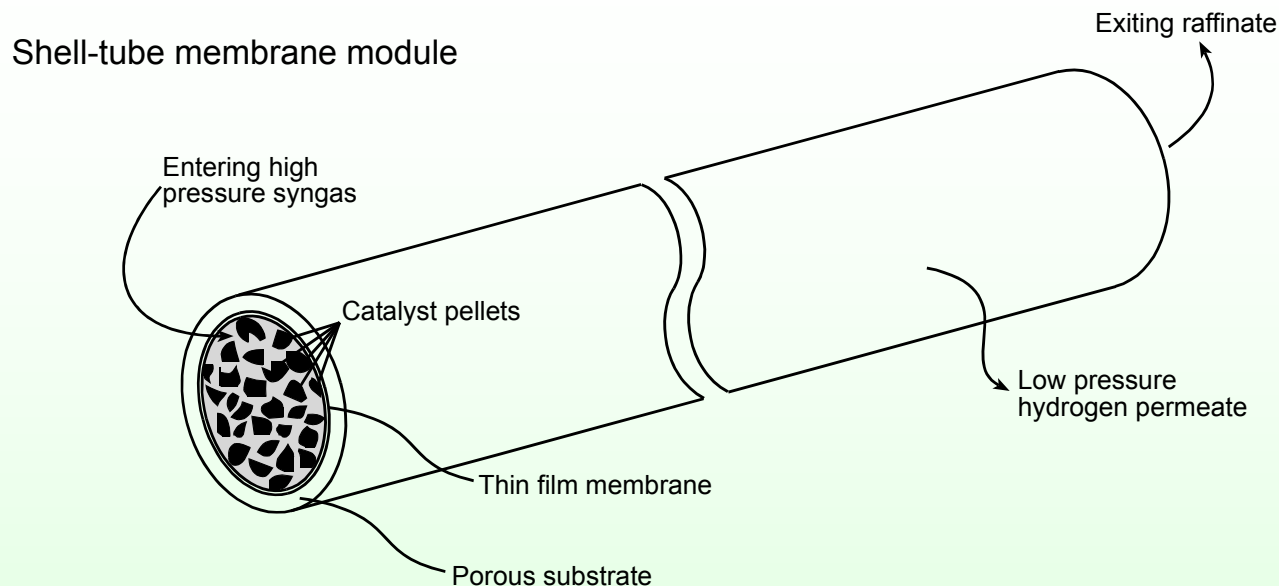
- Use membrane to separate H_2 from the syngas instead of CO_2 .

H₂ Separation Membrane Reactor System

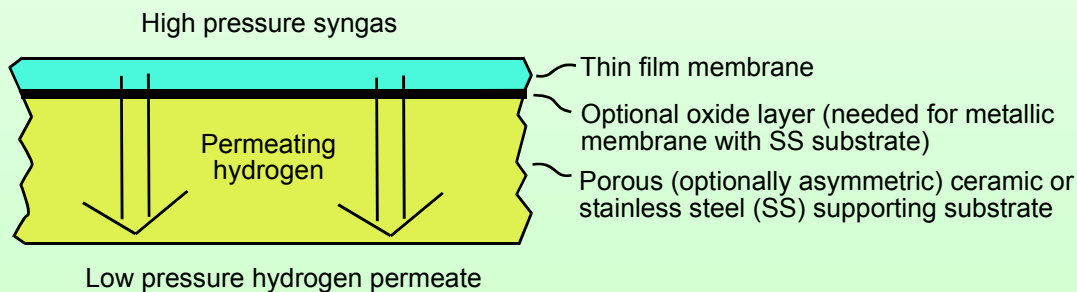


- Employ a H₂ permeable, thin film (10 μm), 60/40% Pd/Cu (sulfur tolerant) dense metallic membrane, configured as a WGS membrane reactor.

Hydrogen Separation Membrane Reactor Concept



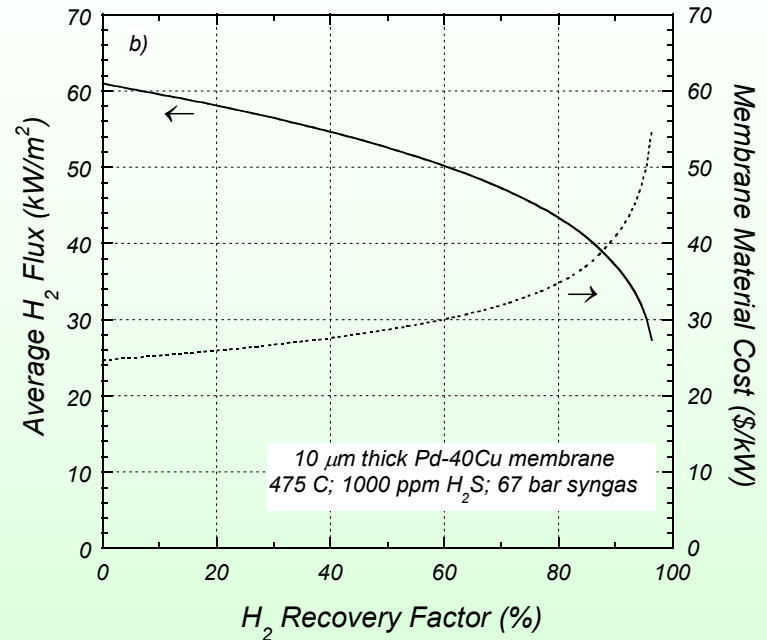
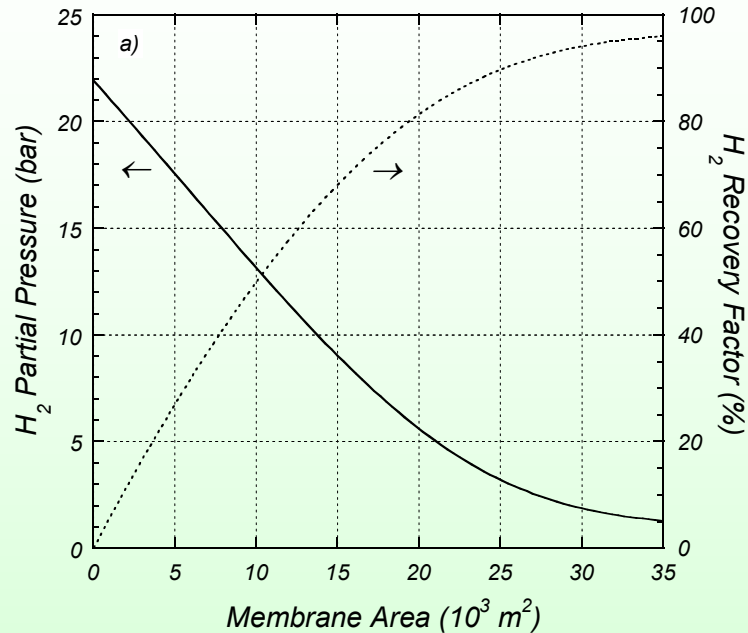
Membrane Structure:



Membrane Reactor 4 1-7-02

- Alternative HSMR design: high pressure, WGS reaction, and membrane *outside* supporting tube, with H_2 permeating to the interior of the tube

Typical Membrane Reactor Performance



- H_2 Recovery Factor (HRF) = H_2 recovered / ($\text{H}_2 + \text{CO}$) in syngas
- HRF increases with membrane area \rightarrow **diminishing returns**
- Membrane costs rise sharply above HRF ~80-90% (no sweep gas)

System Parameter Variations

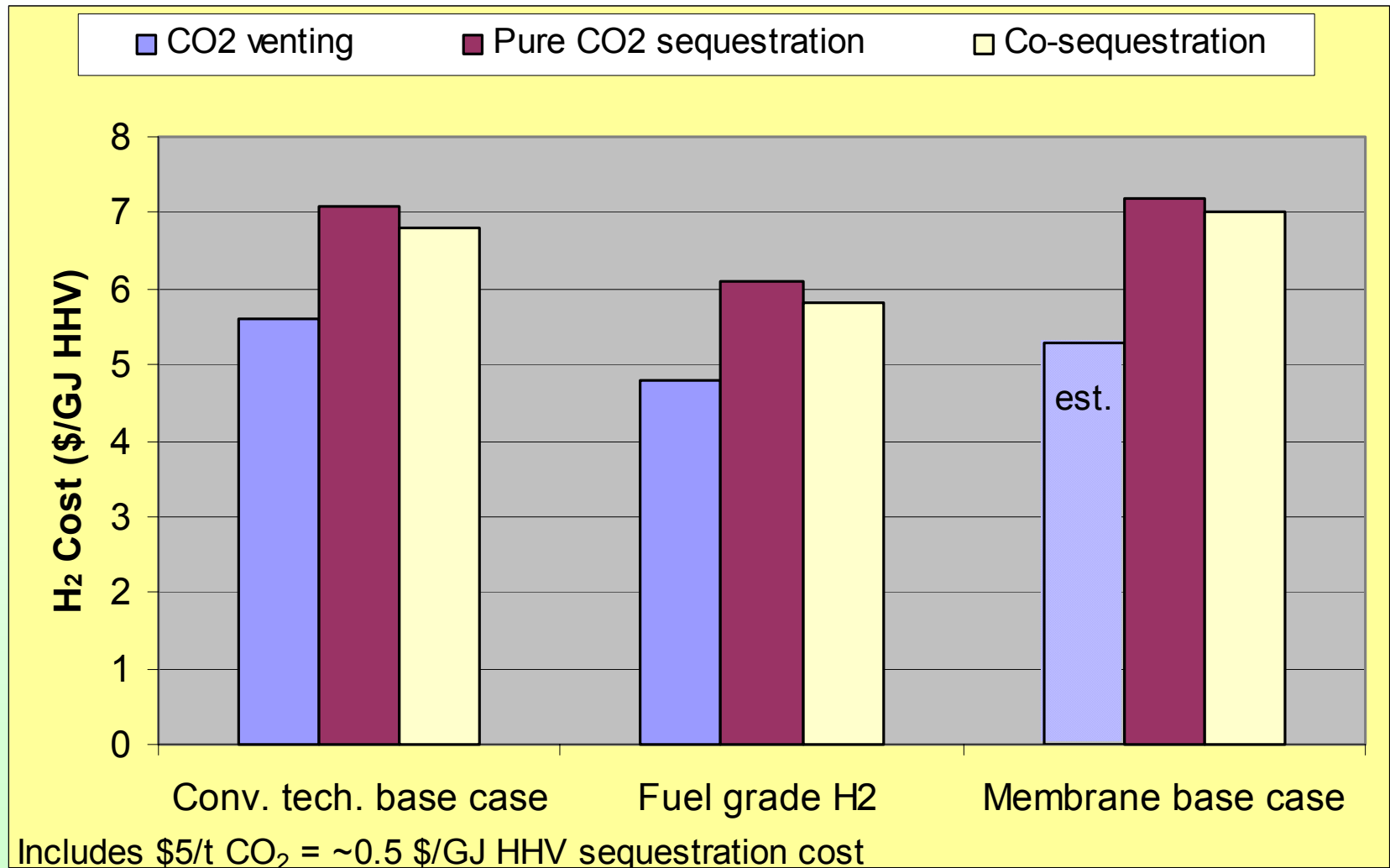
System Performance:

- membrane reactor configuration
- membrane reactor operating temperature
- gasifier/system pressure
- hydrogen purity
- hydrogen backpressure
- hydrogen recovery factor (HRF)
- raffinate turbine technology (blade cooling vs. uncooled)

System Economics:

- membrane reactor cost (and type)
- by-product electricity value
- sulfur capture vs. sulfur + CO₂ co-sequestration

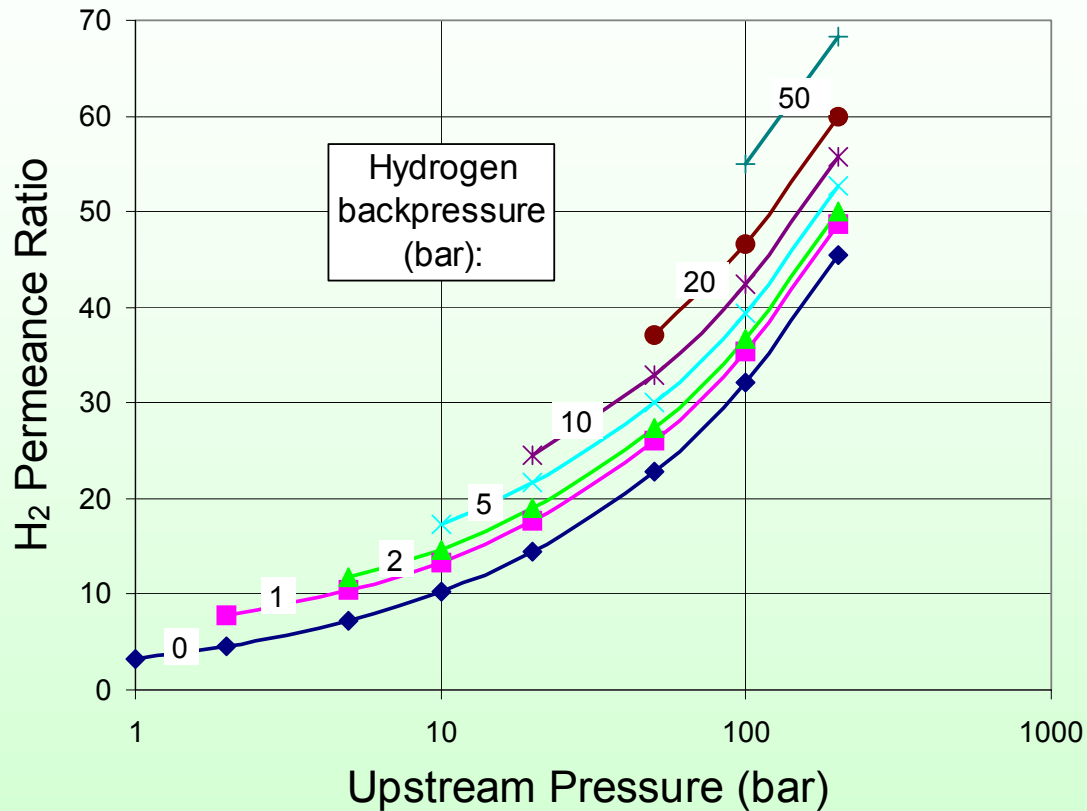
Pd/Cu Membrane-Based H₂ Separation



- Cost of H₂ via Pd/Cu membrane very close to conventional technology.

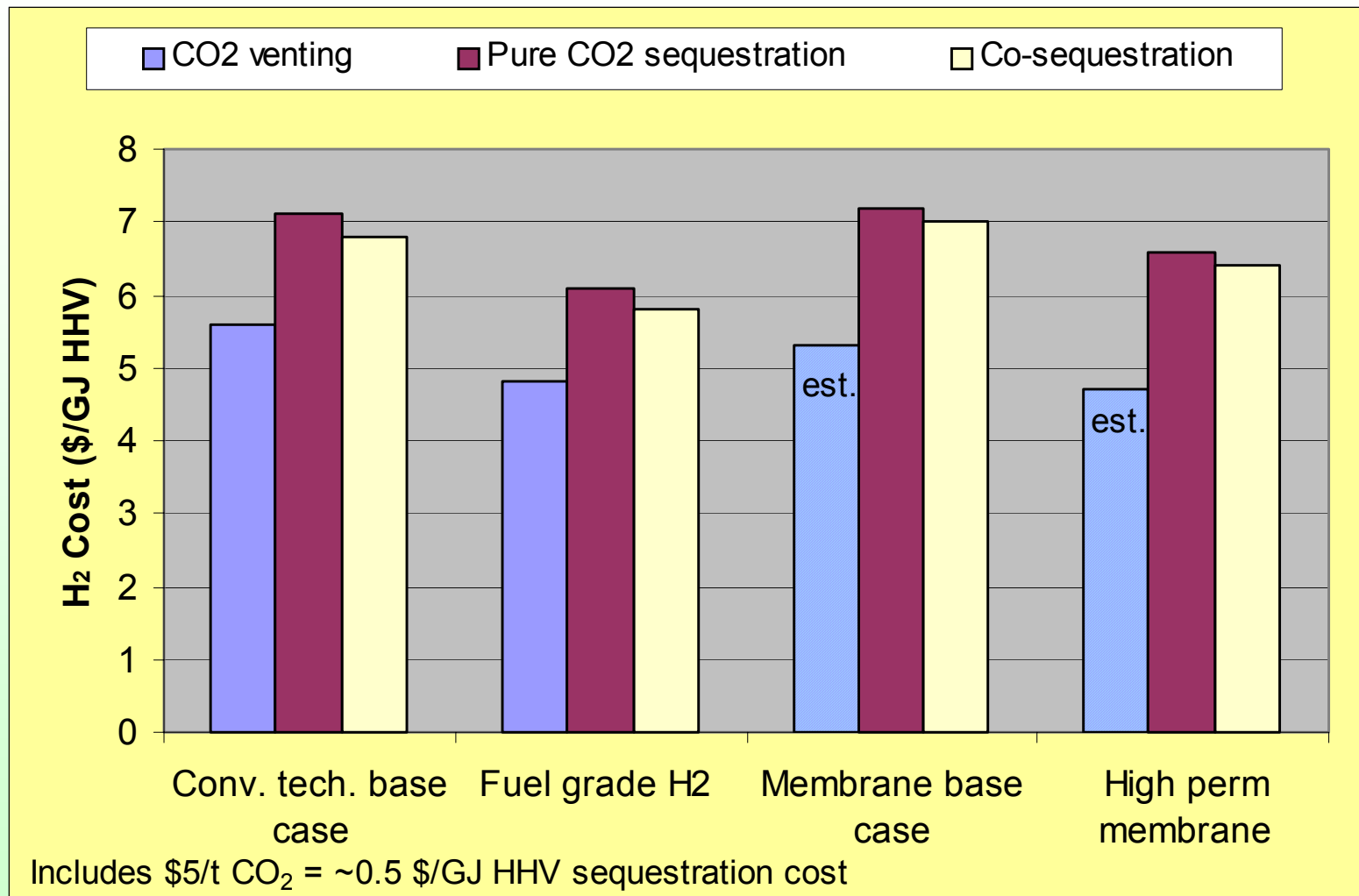
Oak Ridge Molecular Sieving Membrane

- H_2 Permeance Relative to 60/40 Pd/Cu -



- Membrane permeance pressure dependence:
 - ceramic: $(P_{\text{high}} - P_{\text{low}})$ vs. metallic: $(\sqrt{P_{\text{high}}} - \sqrt{P_{\text{low}}})$
- Permeance increase up to factor of ~50 possible. Reduced purity.

Ceramic Molecular Sieving Membrane



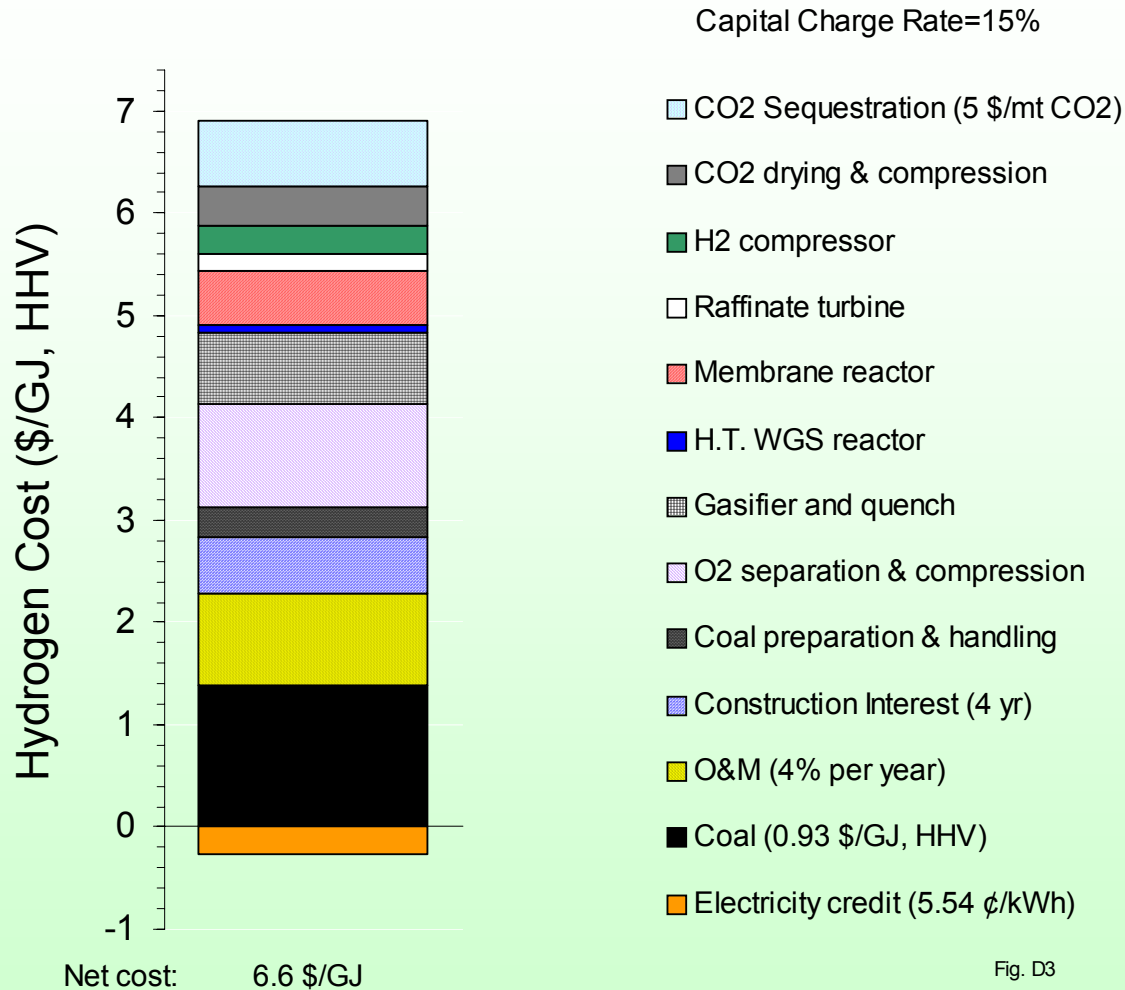
- Preliminary economic comparison, using *same* membrane cost (\$3,000/m²):
H₂ cost lower by ~0.5 \$/GJ HHV (at 70 bar; more for 120 bar gasifier).

Conclusions

- Consistent framework for estimating the performance and cost of converting coal to H₂ and electricity with CO₂ sequestration.
- Investigated membrane-based vs. conventional H₂ separation.
- Parametric investigation of membrane systems shows:
 - H₂ cost via 60/40 Pd/Cu membrane is comparable to that via conventional technology.
 - High permeance microporous membranes offer modest cost reductions (~\$0.6/GJ HHV), but with reduced H₂ purity.
- High H₂ purity is costly; “fuel grade” H₂ can be produced with conventional technology at significantly lower cost (1.0-1.4 \$/GJ).
- Co-sequestration lowers the cost of H₂ (0.25-0.75 \$/GJ HHV), and may provide other environmental benefits (Hg, etc.).
- We plan to extend methodology to study other feedstocks (petroleum residuals, natural gas, etc.) and novel technologies.

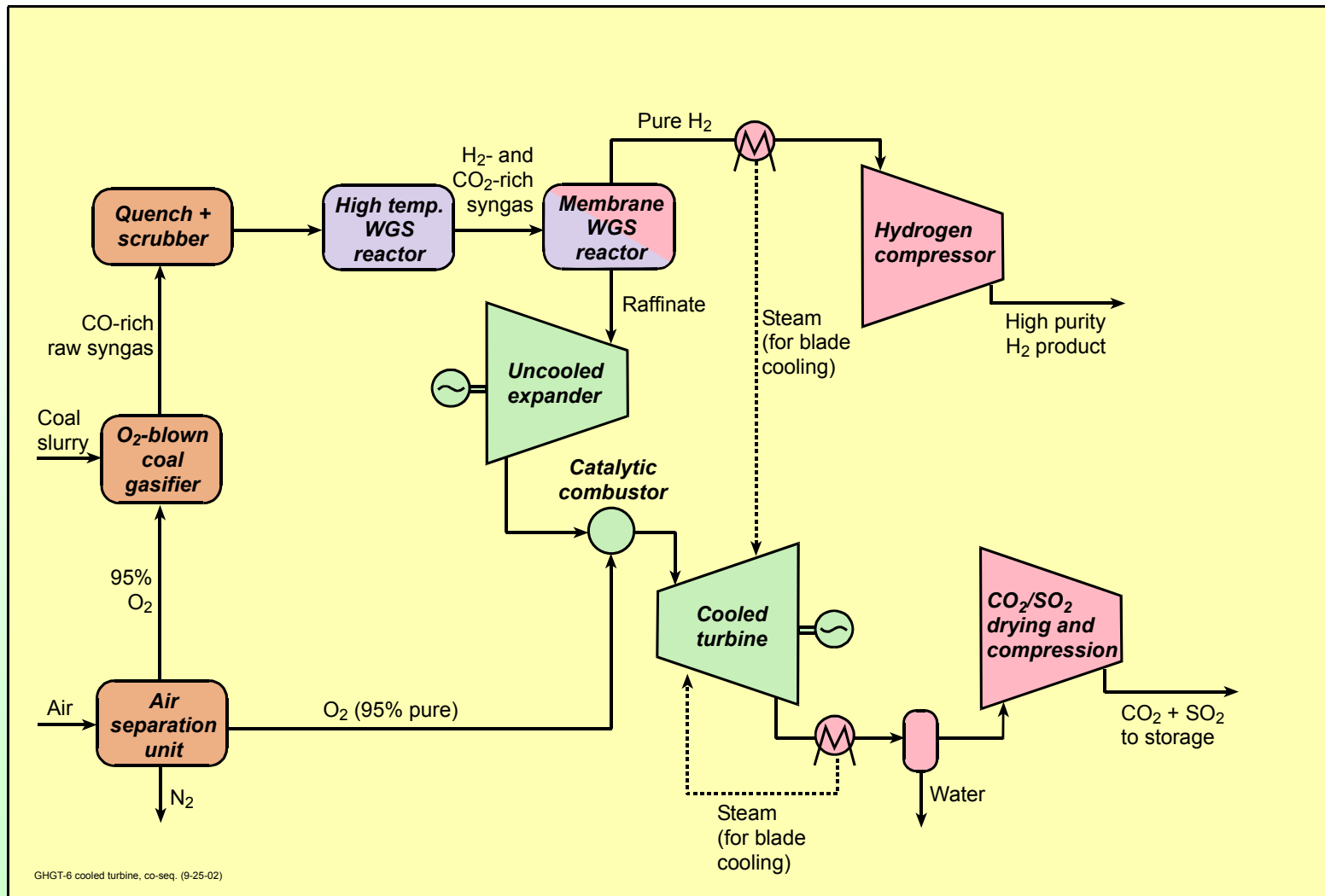
Back-up Slides...

*Example of Disaggregated Cost of H2 Production system
(membrane system...change to conventional)...drop slide?*



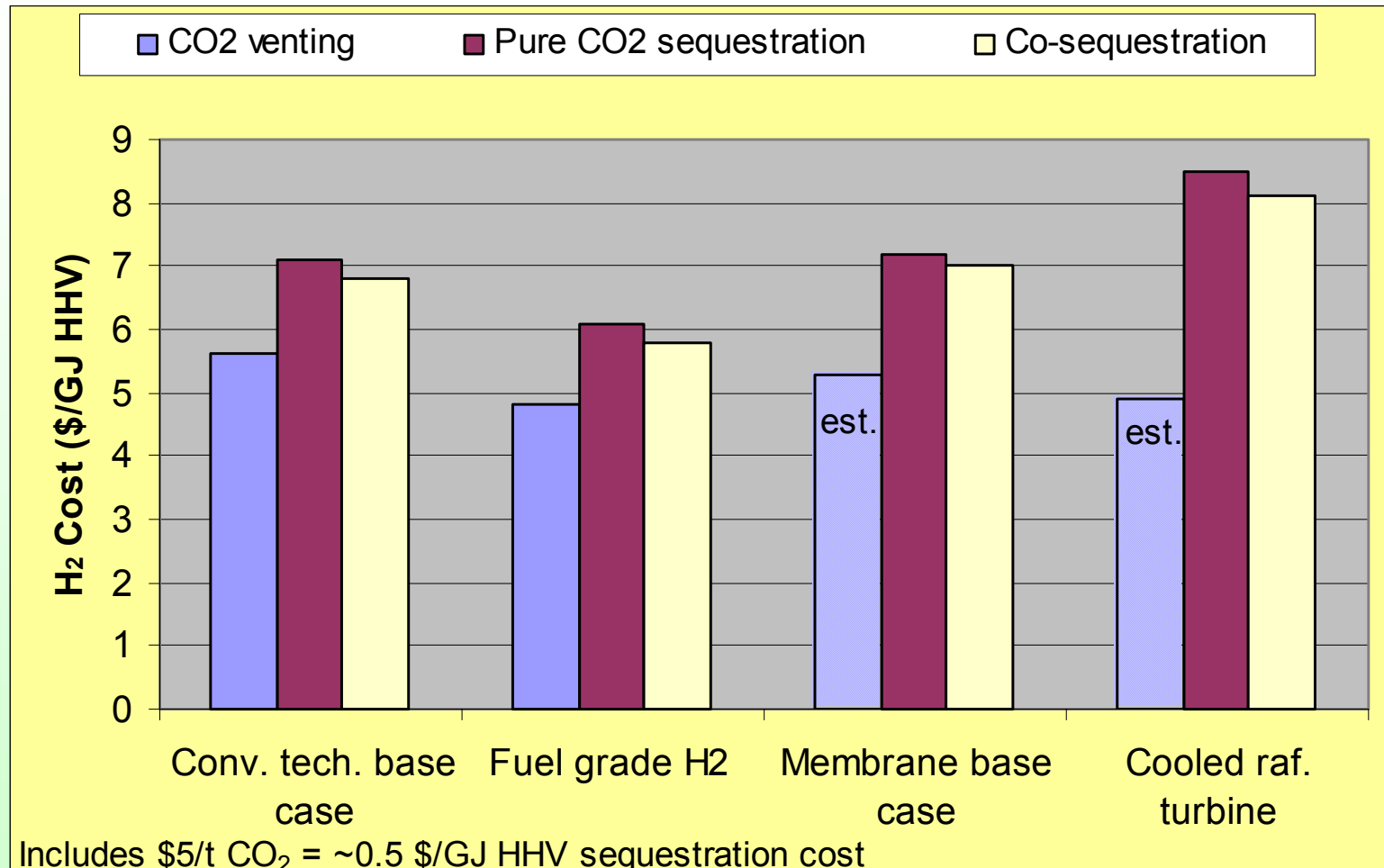
- 70 bar gasifier, 85% HRF, uncooled raffinate turbine, scale: 1 GW_{th} H₂ (HHV)

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 HRF (~60%).

Membrane System with Cooled Raffinate Turbine



- **Cooled turbine (low HRF) system has poor overall efficiency and economics (at low co-product electricity prices, 3 c/kWh)**

The Case for Hydrogen

~1/3	Central station electricity	Centralized (large scale)
~1/3	Transportation	Distributed
~1/3	Other (industrial & residential heating)	Distributed

- Stabilizing atmospheric CO₂ at e.g. 500 ppmv will require *deep* reductions, probably in all 3 sectors.
- Capture, compression, dehydration, and pipeline transport of CO₂ from distributed sources is *extremely* expensive.
- Distributed energy consumption with low CO₂ emissions requires low carbon energy carriers, electricity and hydrogen.
- H₂ likely to play a key role in both the transportation and heating sectors. Relative to electricity:
 - Higher overall efficiency of production & use
 - Easier (less costly) storage

The Case for Coal

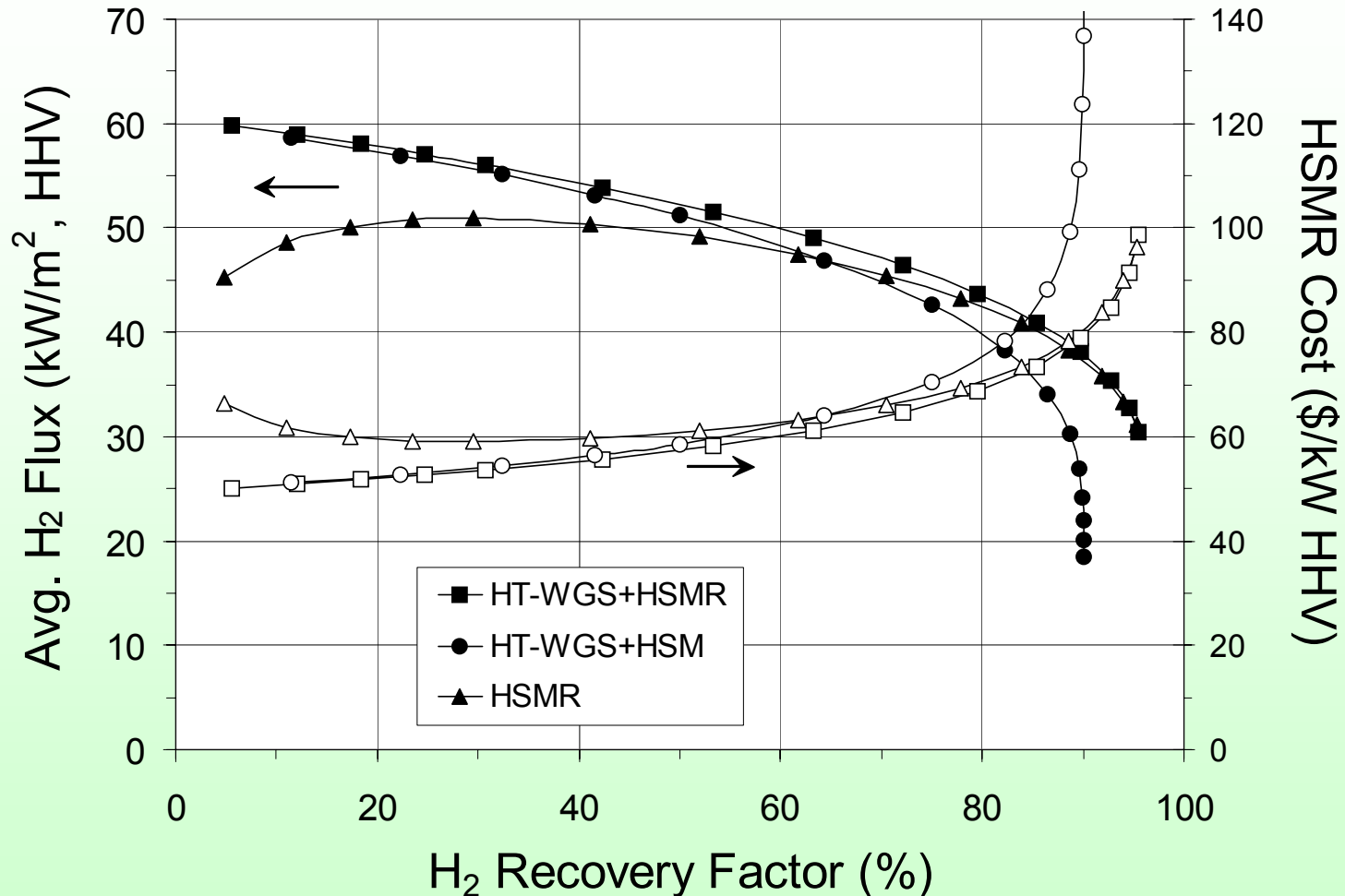
- Abundance of low quality feedstocks (coal, heavy oils, tar sands, etc.) relative to conventional oil and natural gas
- Low feedstock cost relative to natural gas
- China is dependent on coal; US expected to continue being large coal user → is near-zero emission option for coal feasible?
- Air pollution concerns likely to drive coal gasification for power generation—springboard for producing H₂ from coal
- Sulfur, other criteria pollutants, toxics (e.g, Hg) pose major challenges in H₂/electricity manufacture; gasification facilitates low emissions
- Residual environmental, health, and safety issues of coal mining and other low-quality feedstocks

Some Interesting Results

	<i>Description</i>	<i>CO₂ venting</i>		<i>Pure CO₂ sequestration</i>		<i>CO₂-S Co-seq.</i>
		η_{eff} (%)	\$/GJ	η_{eff} (%)	\$/GJ	\$/GJ
Conv. Tech.	<i>Base case</i>	71.6	5.6	69.4	7.1	6.8
	<i>Fuel grade H₂</i>	75.5	4.8	74.7	6.1	5.8
HSMR-Based System	<i>Base case</i>	75	5.3	69.1	7.2	7.0
	<i>Cooled raf. turbine</i>	66	4.9	57.8	8.5	8.1
	<i>High perm HSMR</i>	76	4.7	69.9	6.6	6.4

- Sequestration lowers efficiency and increases costs
- Co-sequestration has potential to lower costs
- H₂ purity comes at a significant cost. Fuel grade (~94% H₂) can be produced at a significantly lower cost in a system with significantly lower capital cost.
- 60/40% Pd/Cu membrane system not obviously better than conventional.
- Cooled turbine (low HRF) system has poor efficiency and economics (at low co-product electricity prices, 3 c/kWh)
- High permeance membrane (at 70 bar) might yield only modest improvements.

Effect of HSMR Configuration



- In this system, with an upstream WGS reactor, a membrane *reactor* not obviously necessary for good system performance.

Hydrogen Cost vs Gasifier Pressure

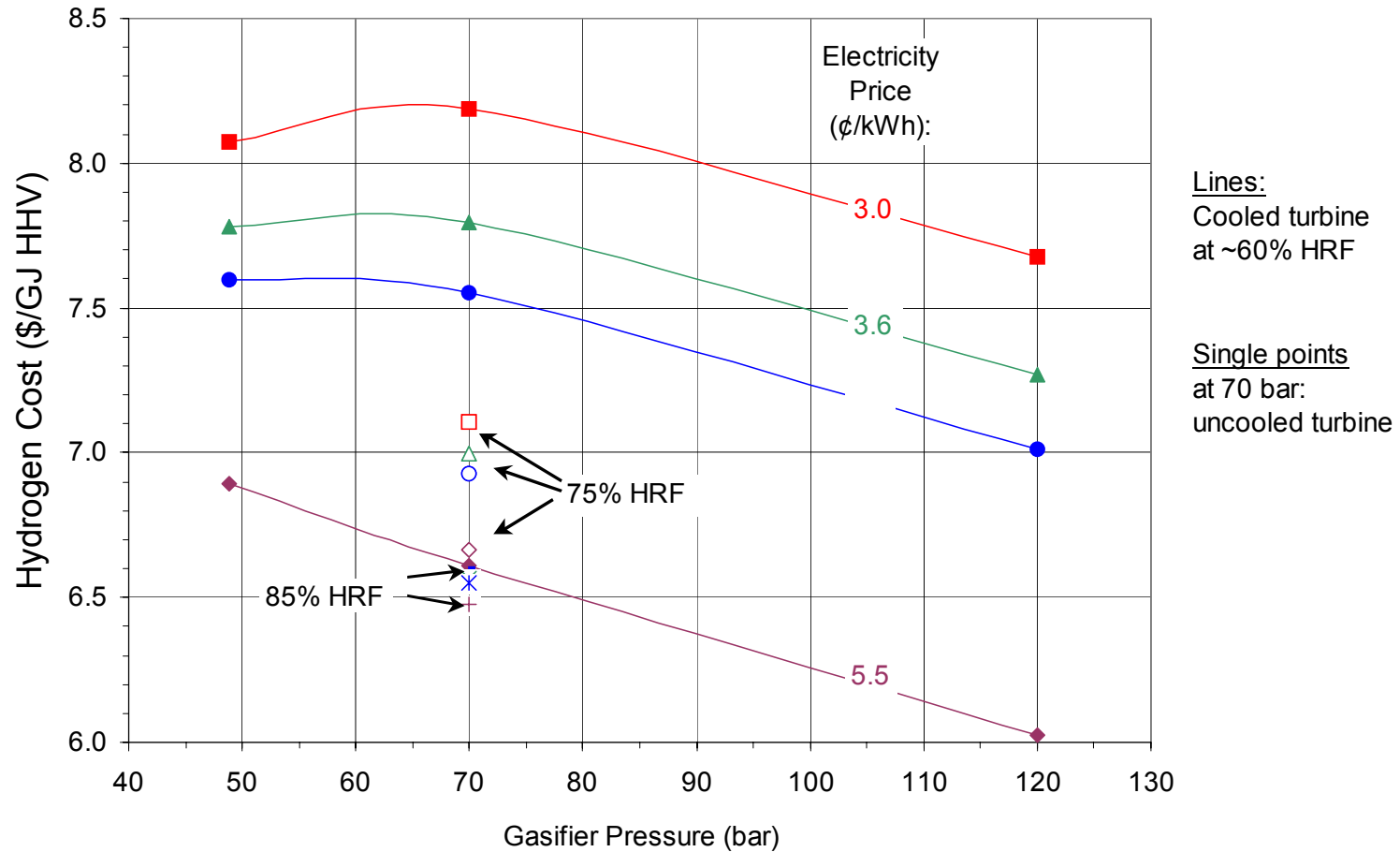


Fig. H2

- Increasing pressure can significantly reduce cost of decarbonized hydrogen
- Cooled raffinate turbine typically requires low HRF to realize high TIT
- Uncooled turbine/high H₂ recovery: greater promise, esp. at low elec. prices

Cost of H_2 Compression and HSMR vs. H_2 Backpressure

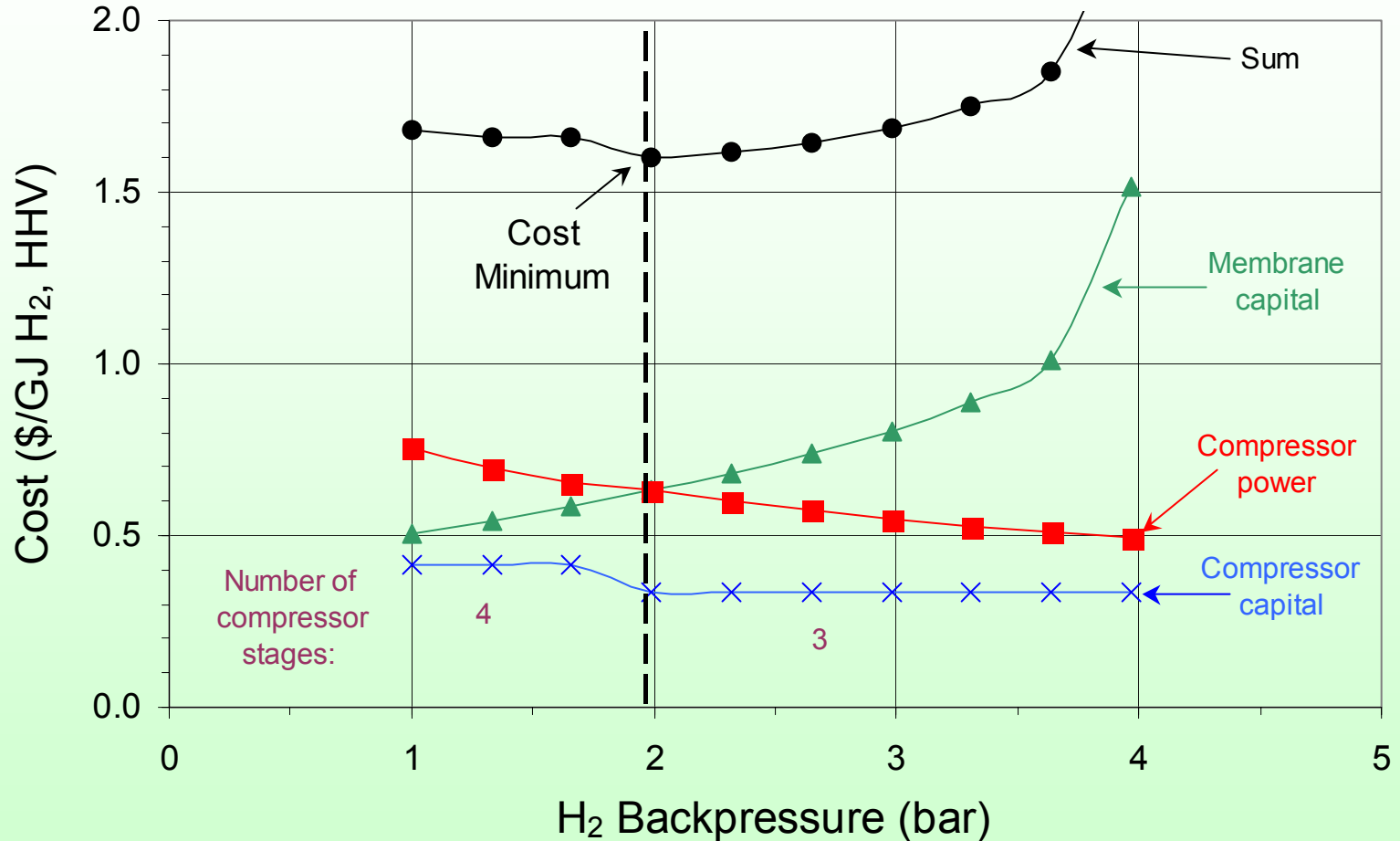


Fig. G4b

- Broad cost minimum seen here (not always) at low H_2 backpressure

Effects of H₂ Recovery and Electricity Price

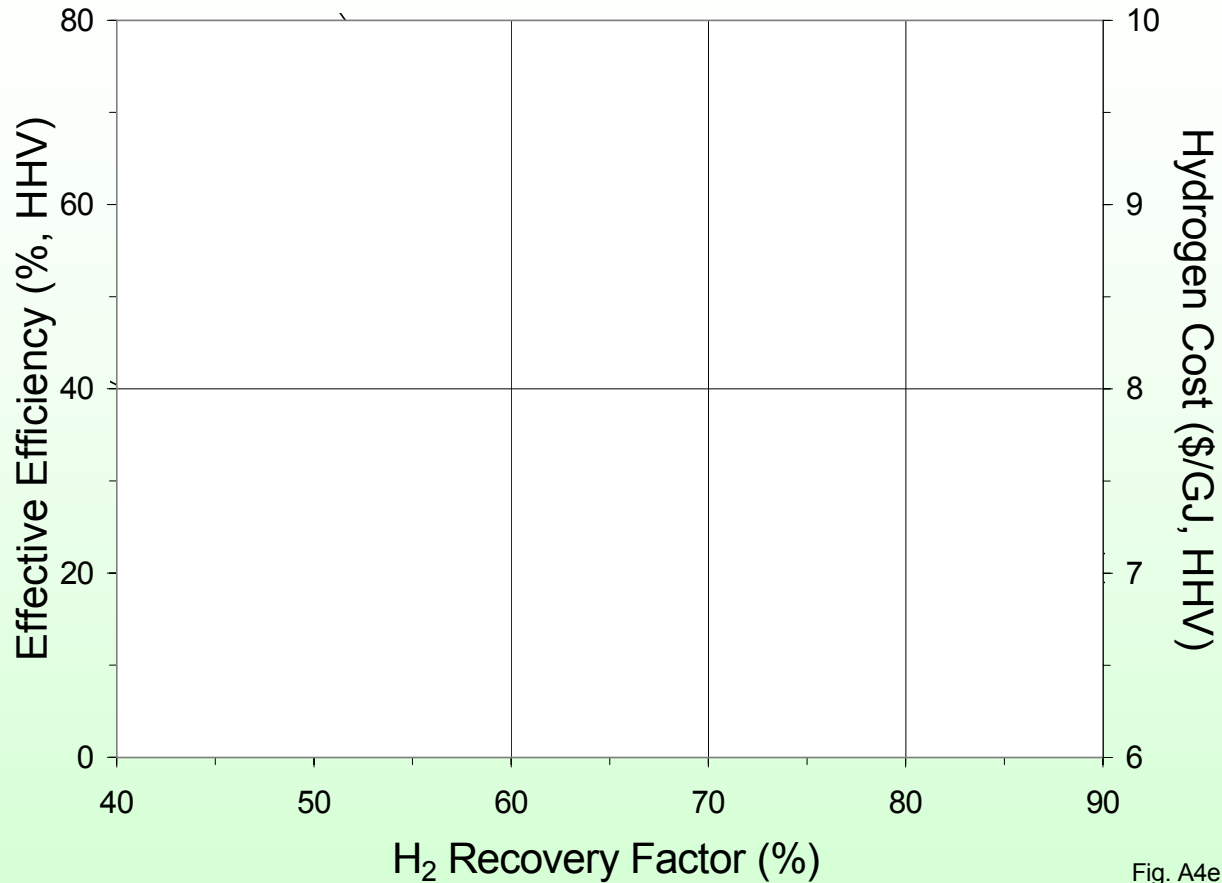
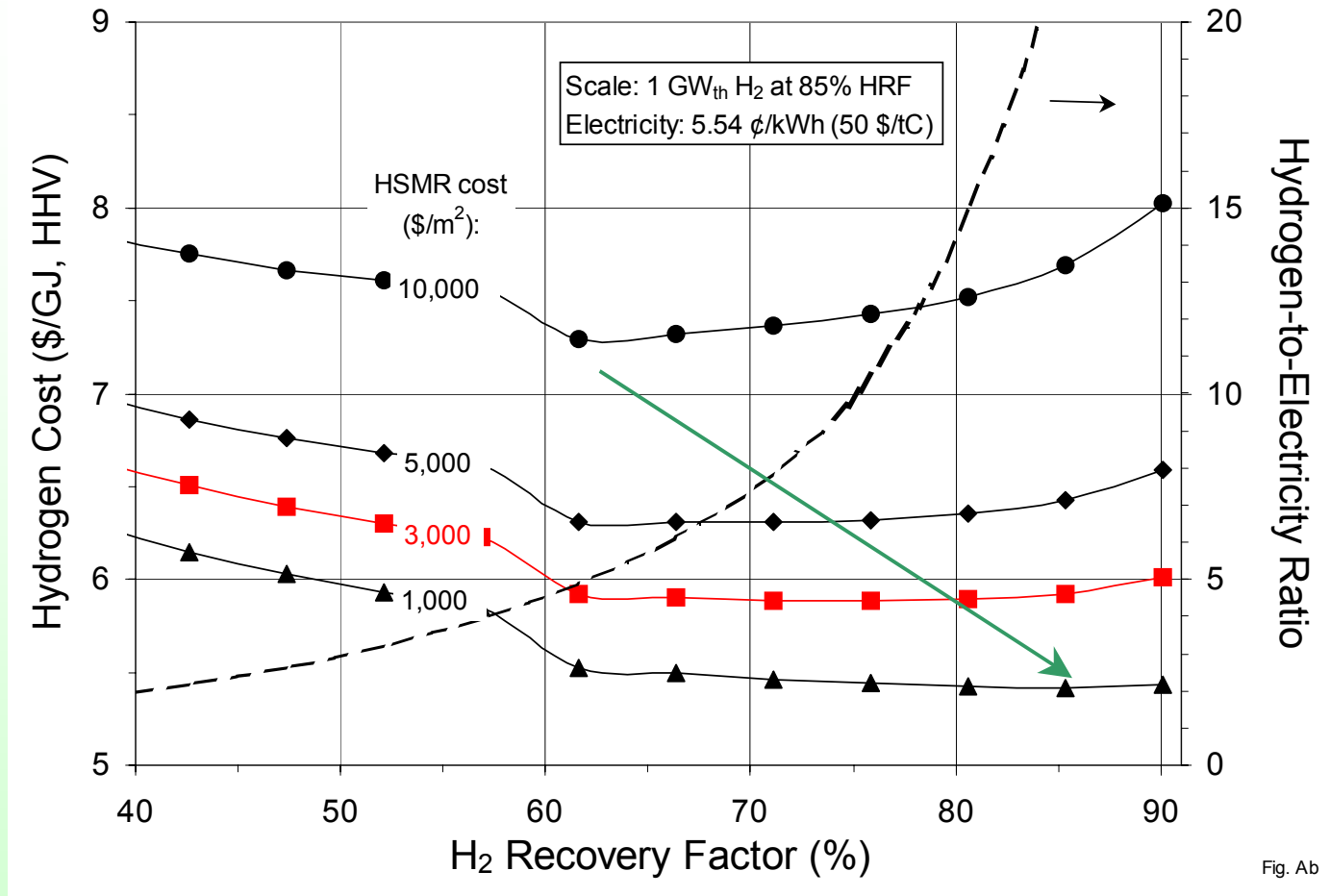


Fig. A4e

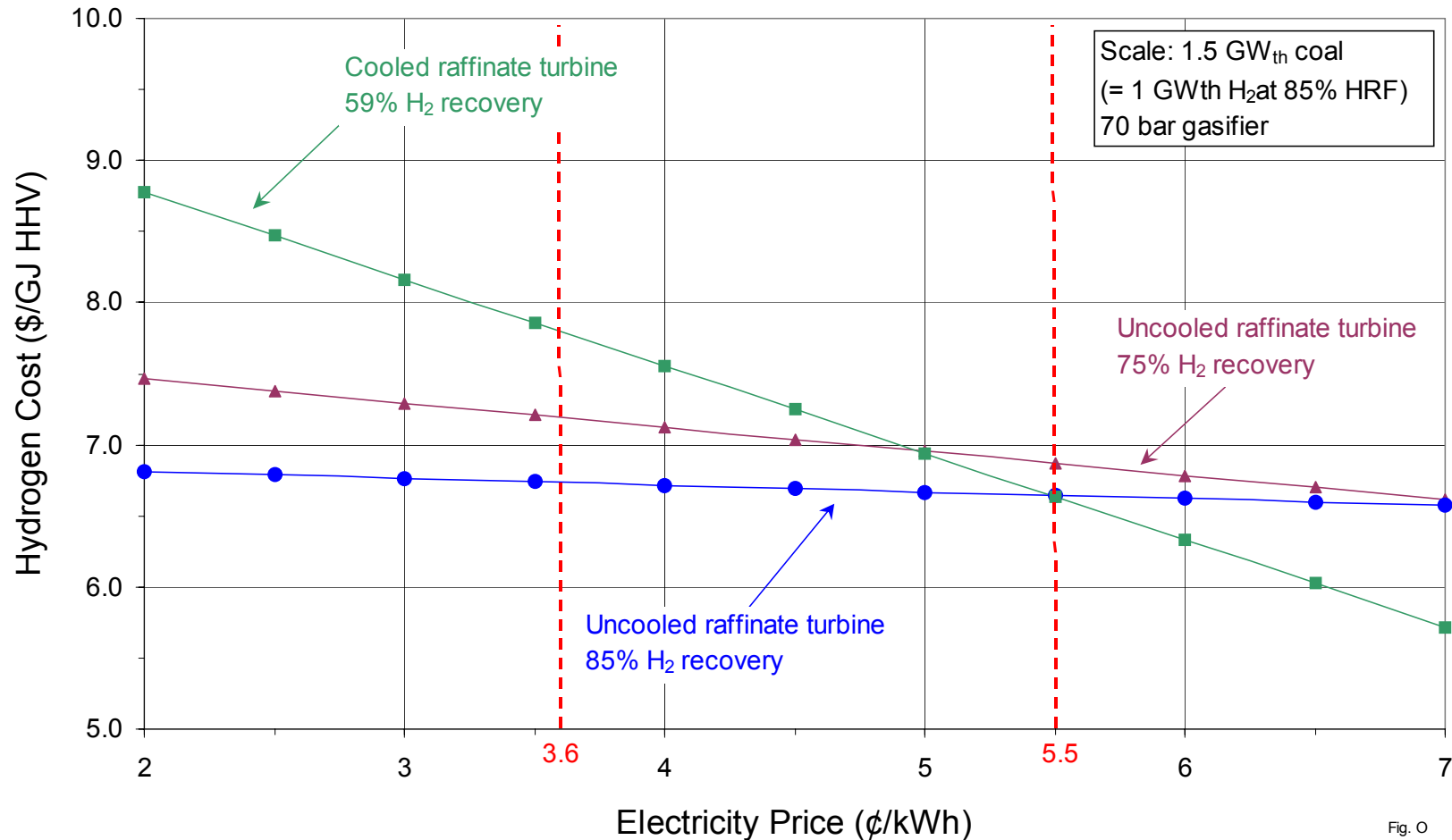
- Efficiency rises monotonically with increasing HRF
- Low prices for co-product electricity favors production of H₂ over electricity
- At high electricity prices, H₂ cost is insensitive to HRF in the 60-90% range

Effects of H₂ Recovery Factor and HSMR Cost



- A five-fold variation in HSMR cost alters the H₂ cost by ~\$1/GJ (HHV)
- H₂ costs exhibit a broad minimum with respect to HRF (from ~60-90%)
- As HSMR costs decrease, optimal HRF increases (long green arrow)

Effects of Electricity Price and Turbine Technology



- 3.6 ¢/kWh: electricity from GTCC fired by natural gas (cost: 3.4 \$/GJ HHV)
- 5.5 ¢/kWh: breakeven price for electricity from coal IGCC - at carbon tax of \$50/tC - when CO₂ sequestration becomes competitive with CO₂ venting