Perspectives on Hydrogen from Fossil Fuels for CO_2 Mitigation

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The Carbon Mitigation Initiative (CMI) at Princeton University, 2001-2010

- CMI Project Areas:
  - *Carbon capture (Kreutz, Larson, Ogden, Socolow, Williams):* production, distribution, and utilization of electricity and H_2 from fossil fuels.
  - *Carbon storage (Celia):* modeling CO_2 storage in and leakage from saline aquifers; emphasis on risk assessment.
  - *Carbon science (Pacala, Sarmiento, GFDL):* global climate modeling of CO_2 in the atmosphere, oceans, and land.
  - *Carbon policy (Bradford, Oppenheimer):* Kyoto alternatives, stabilization targets, GH damage functions.
  - *Integration:* economic implications of delayed action, knowledge about trajectories, optimal emission paths.
- Funding: 15.1$ from BP, 5 M$ from Ford

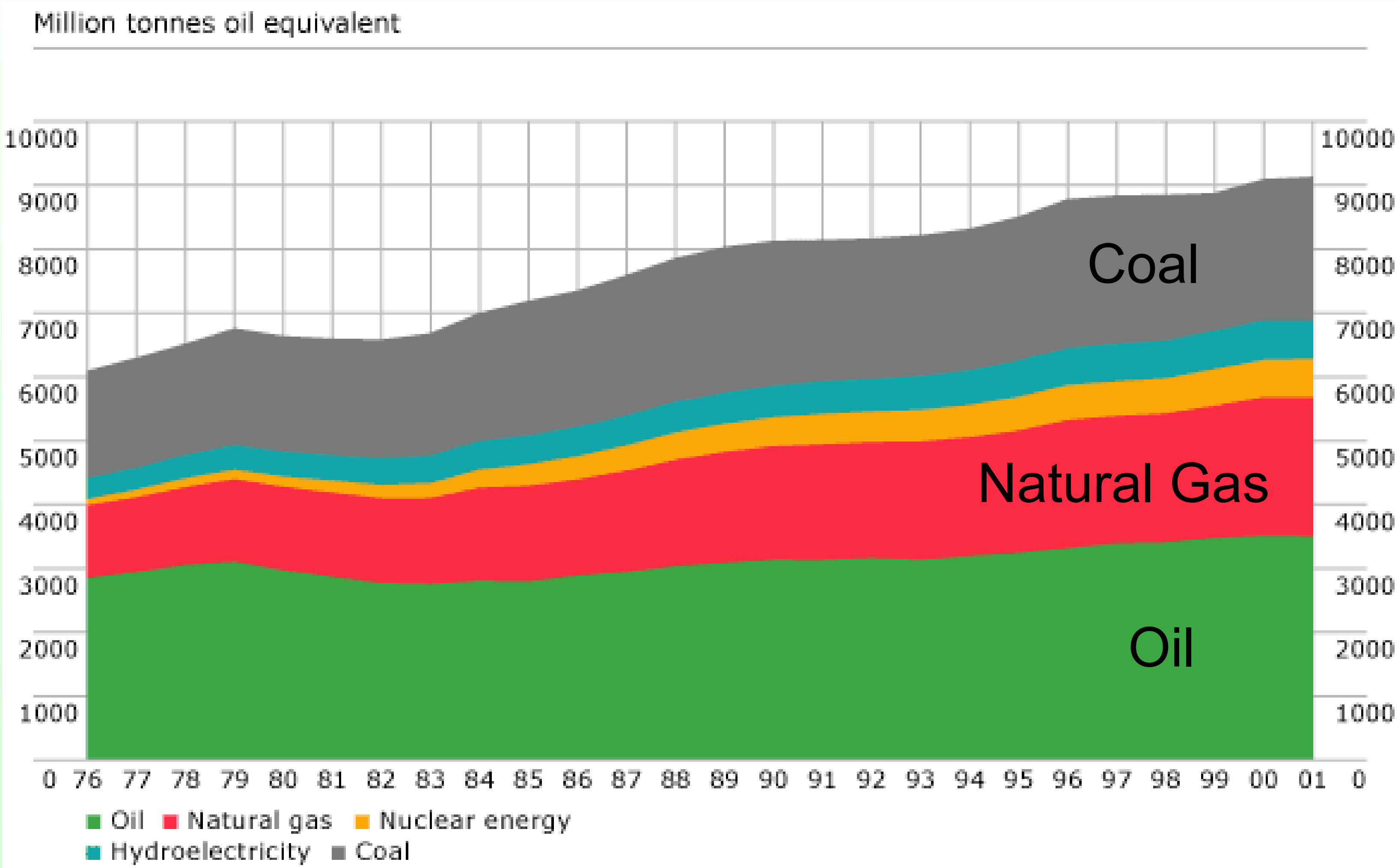
Talk Outline

- How H_2 might fit into the problem of global carbon emissions.
- Some ongoing work at Princeton relating to H_2 production and distribution.

Point of Departure

- The greenhouse effect is real, and growing.
  - It’s a big problem, requiring large changes.
- We want to mitigate its effects, to stabilize CO_2 concentrations at some level, e.g. 550 ppmv, but
  - We don’t want to curtail economic growth.
- We seek to minimize the costs (economic, societal, etc.) of mitigation.
  - Advantages may result from large changes.
- We balance GH costs against mitigation costs.
  - Evolving process: science + policy/politics.

World Consumption of Primary Energy



From: http://www.bp.com/centres/energy2002/primary.asp#

Fossil Fuels are…

- plentiful:

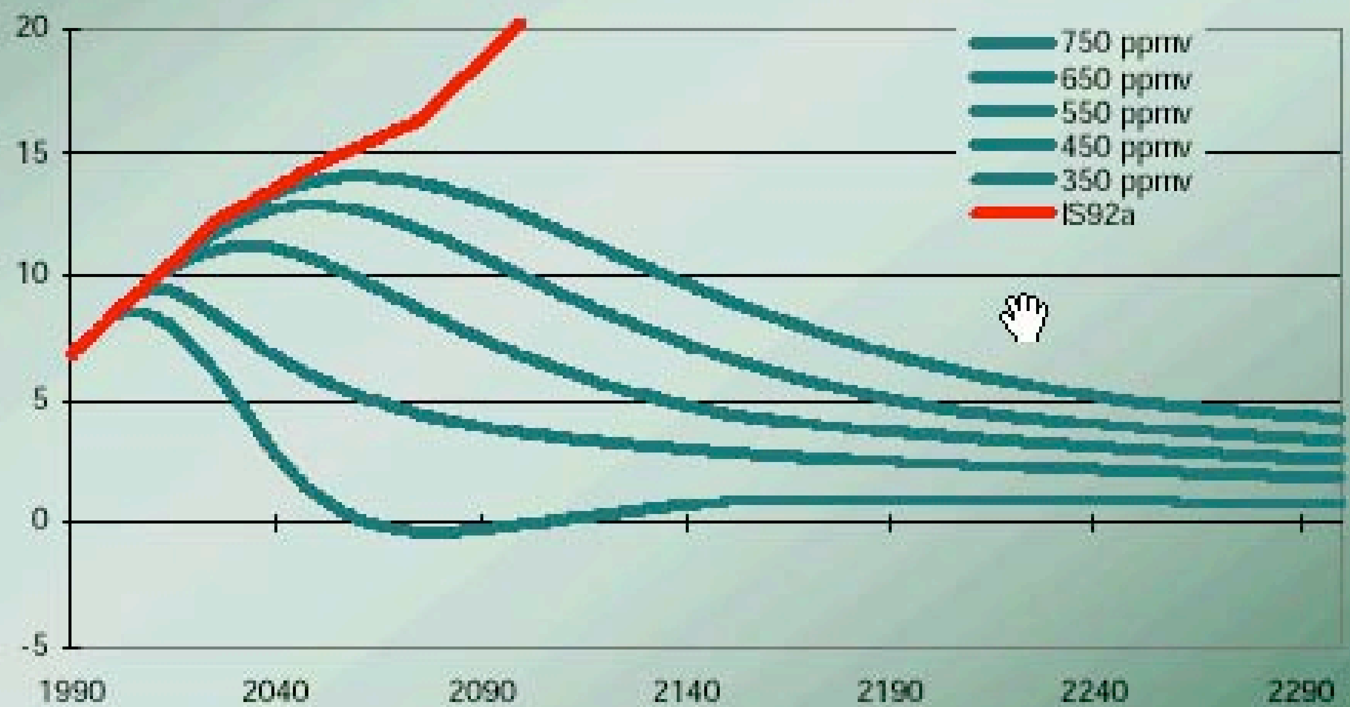
Global Fossil Carbon Resources (Gt)	Resource Base	Additional
Conventional oil (85 wt. % C)	250	
Unconventional oil	440	1550
Conventional natural gas (75% C)	240	
Unconventional natural gas	250	220
Clathrates		10600
Coal (70% C)	3400	2900
Total	***4600***	***15300***

- the primary cause of greenhouse warming.
- the largest source of primary energy (X% worldwide)
- likely to continue to be extremely important for many decades until other, low carbon sources (renewables, nuclear energy) become more mature, widespread, and less expensive.

Stabilizing Concentrations

Means Emissions Must Ultimately Begin a Long-term Decline …

Emissions Trajectories Consistent With Various Atmospheric CO2 Concentration Ceilings

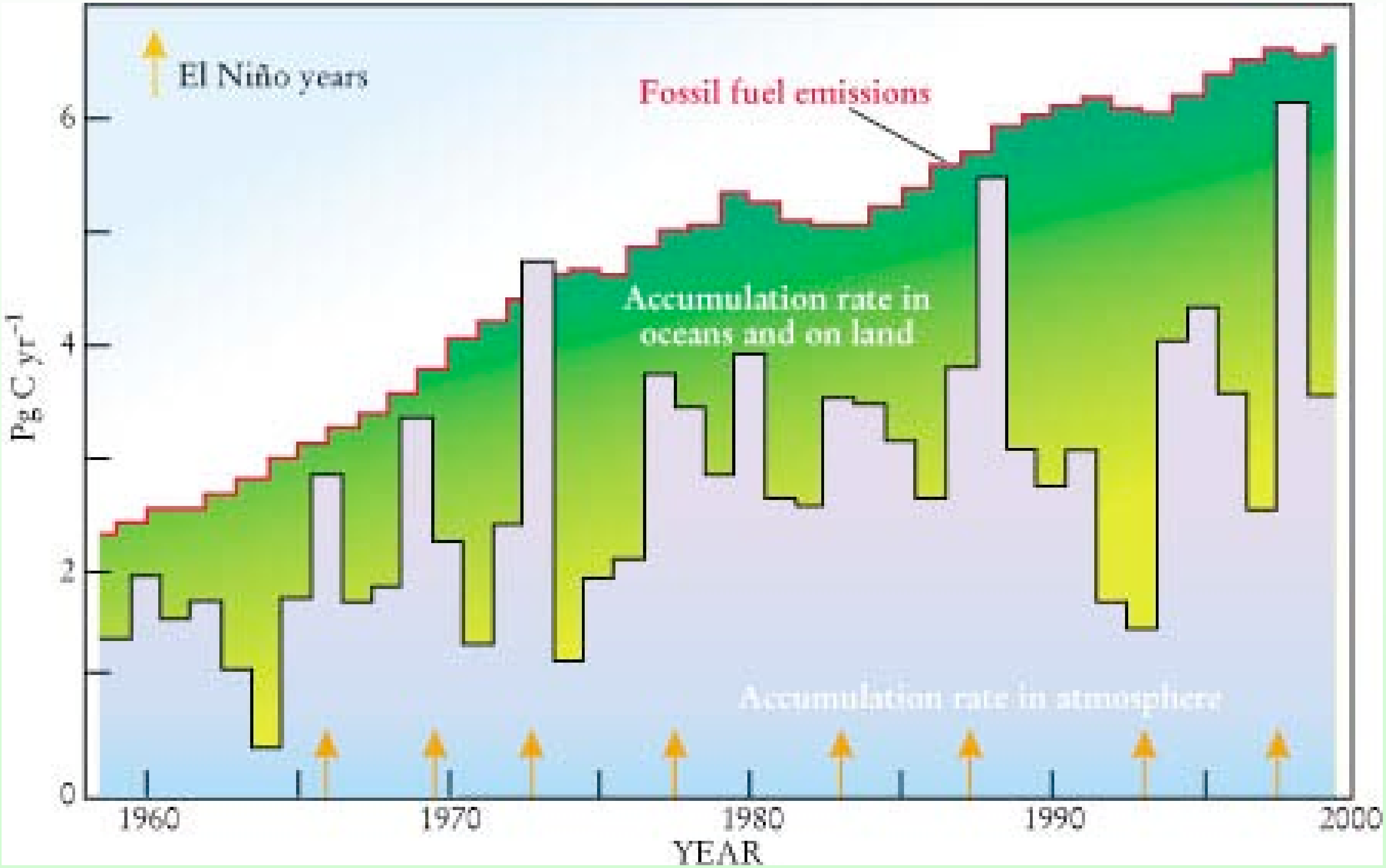


Battelle

Pacific Northwest National Laboratory

The Joint Global Change Research Institute

Growth Rate of Carbon Reservoirs



Use of Fossil Fuels in a Carbon-Constrained World

- Stabilization of CO_2 concentrations (e.g. 550 ppmv) will require huge reductions in CO_2 emissions over the next century.
- Thus, continued, large scale use of fossil fuels will *require* carbon capture and storage (CCS).
- Large scale generation of carbon-free energy carriers, electricity and hydrogen, from fossil fuels is commonplace.
- CO_2 separation/capture can be accomplished with proven, commercial technology.
- Very large scale CO_2 *storage* is the big unknown.

Second Point of Departure

- In our work, and in this talk, we *assume*:
  - Widespread, large scale CO_2 storage, e.g. in saline aquifers, will be a viable - and not too expensive - undertaking.
  - Fossil fuels are going to play a major role for the next 50-100 years.

- The extent of fossil fuel use will depend on a host of factors (discussed at this conference):
  - *Actual* CO_2 storage costs,
  - Carbon taxes/policy,
  - Costs of competing low carbon energy sources,
  - Etc.

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

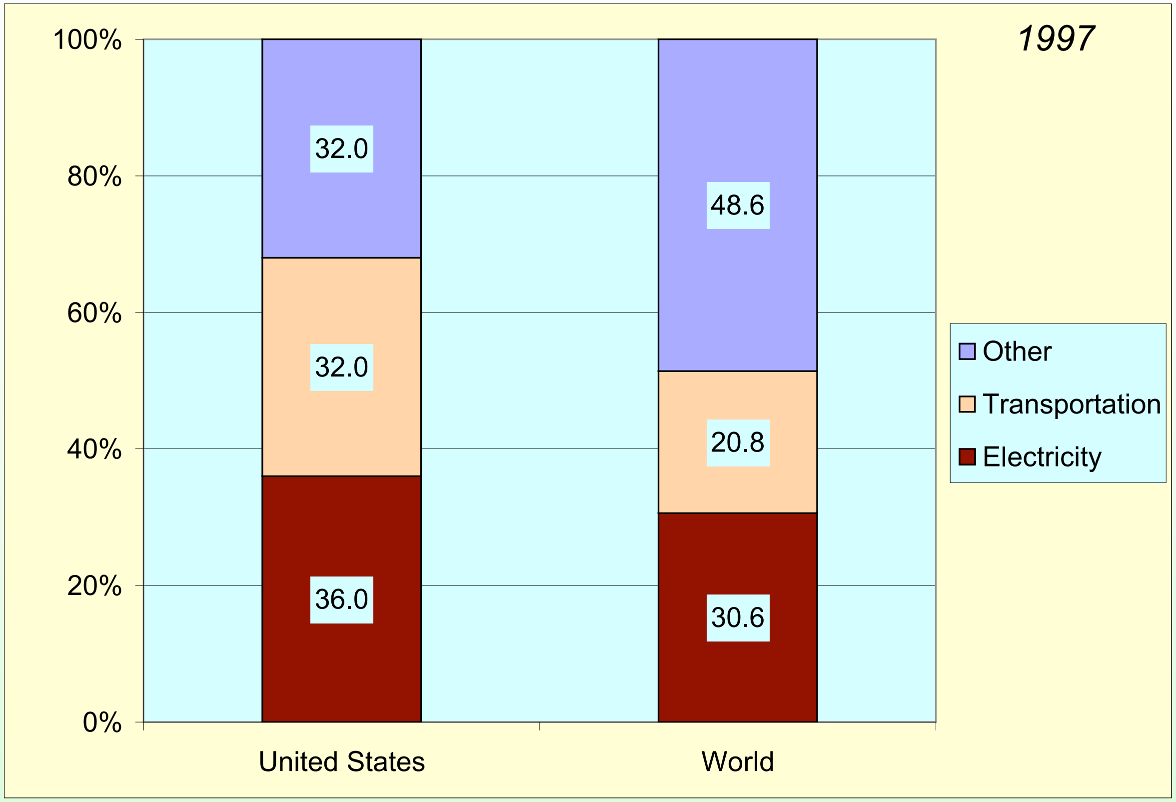
Global Capacity For CO_2 Storage In Deep Saline Aquifers

- 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 [*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

CO_2 Disposal Experience

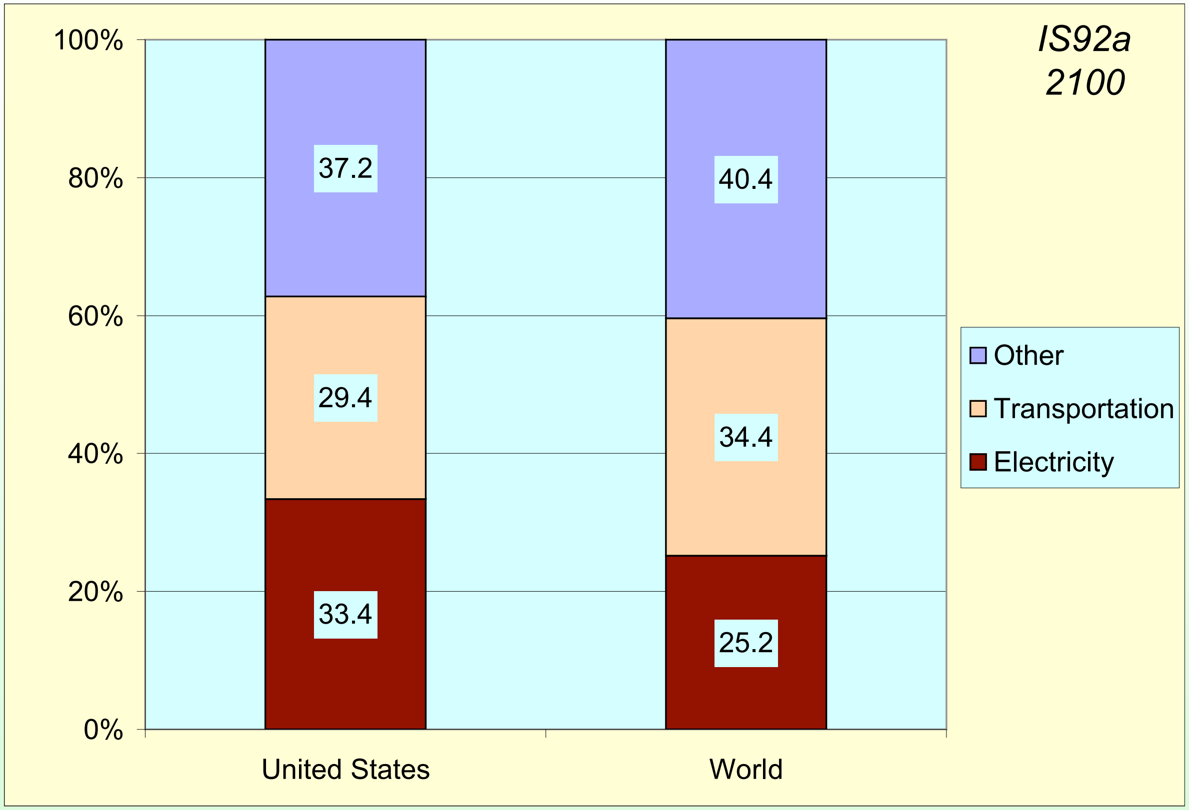
- *Enhanced oil recovery:* 74 projects worldwide injecting 30 MMt CO_2/y; 4% of US oil so produced—mostly using CO_2 from natural reservoirs (> 3000 km of CO_2 pipelines in US), but Weyburn (Canada) uses 1.5 MMt/y of CO_2 piped 300 km from North Dakota coal gasification plant
- *Enhanced coal bed methane 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

Current CO_2 Emissions



- Centralized power generation is relatively easy to decarbonize.
- 2/3 – 3/4 of CO_2 emissions from *distributed* sources: transportation and "other" (primarily industrial, commercial, and residential heating).

Projected CO_2 Emissions

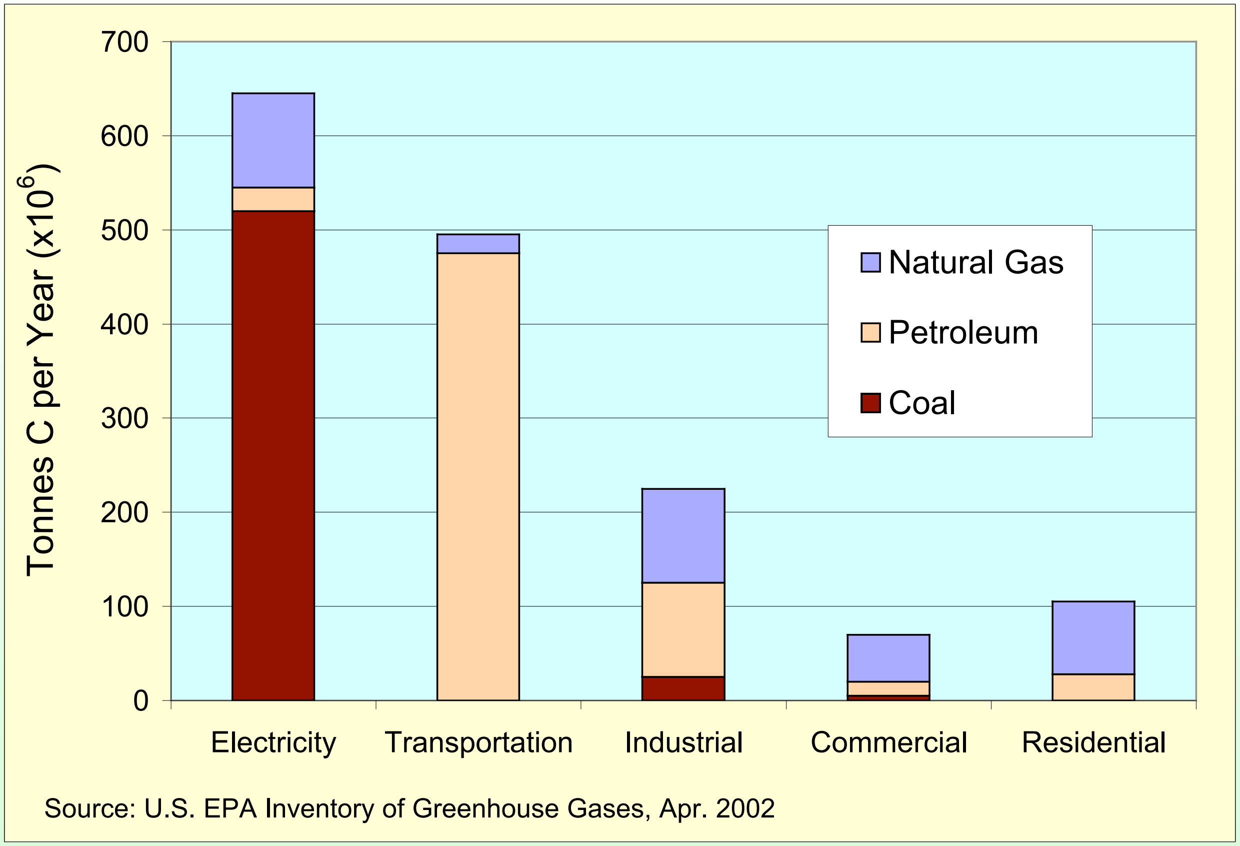


- Similar story under IPCC IS92a projections.
- These ratios obviously depend on competition between sectors.

What to do about CO_2 Emissions from Distributed Consumption of Fossil Fuels?

- Switch to “low-carbon” electricity (from fossil fuels with *CCS*, nuclear, or renewables):
  - Difficulties with storage (transportation) and efficiency (heating) will limit adoption. By how much?
- Switch to “low-carbon” hydrogen, from:
  - Centrally “decarbonized” fossil fuels with *CCS*,
  - Biomass (without - or with - *CCS*),
  - Nuclear, via advanced thermochemical cycles,
  - Electrolysis using low-carbon electricity.
    - Efficiency losses vs. transportation costs
  - *H*+*T* require H_2 distribution, *T* requires H_2 onboard storage
- CO_2 capture and storage from air.

Annual U.S. Carbon Emissions (2000)



- Power generation with CCS ~100-200 $/tonne C.
- Transportation sector via H_2…1000 $/tonne C?

Drivers for the H_2 Economy

- H_2 is abundant and can be utilized relatively and cleanly (via combustion, electrochemistry)
- Energy security
- Air pollution
- Climate change
- Common carbon-free energy carrier from:
  - renewables
  - fossil fuels
  - nuclear power

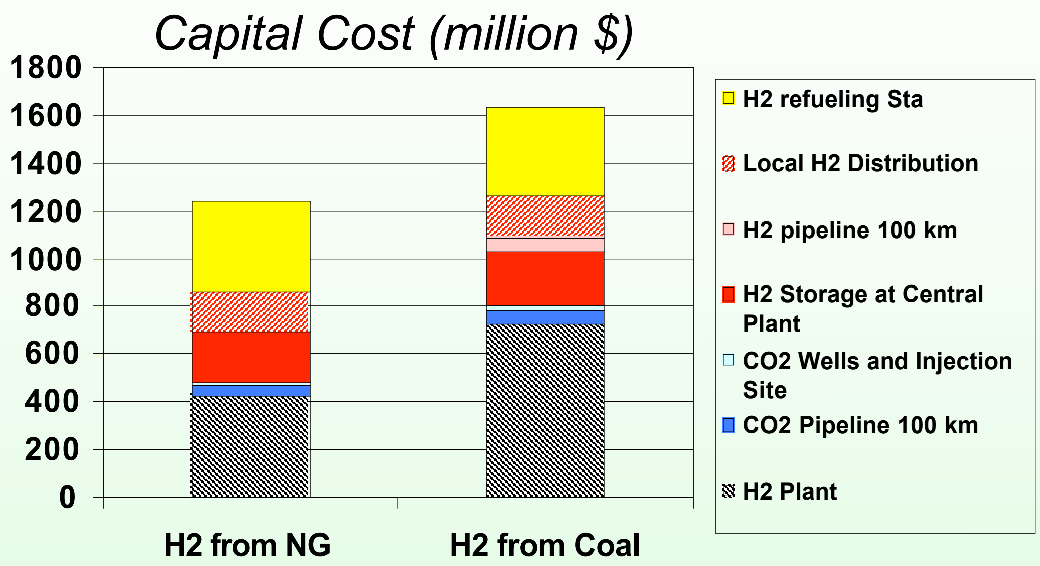
Difficulties with the H_2 Economy

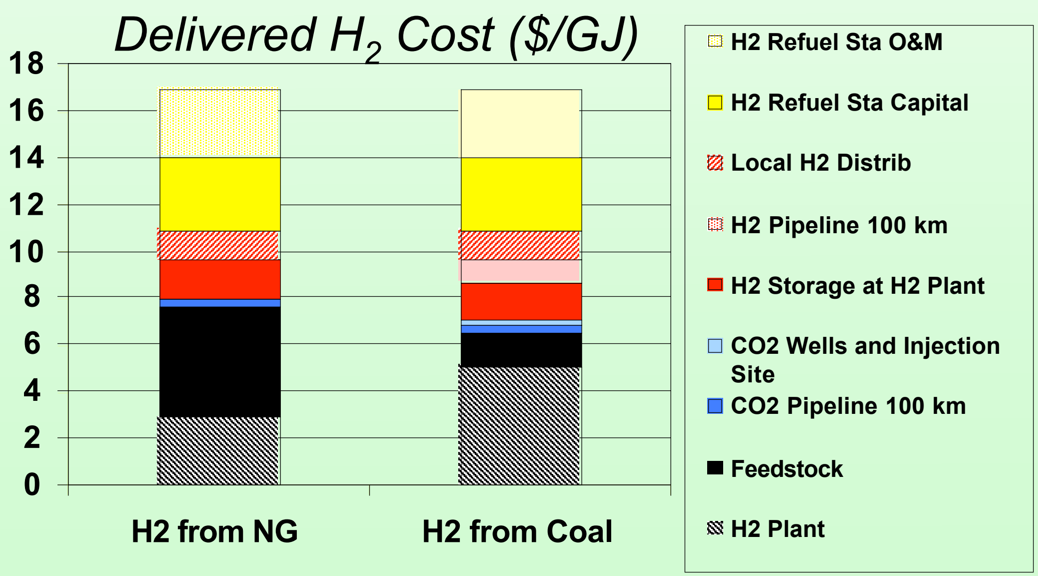
- Efficiency losses during production
- Cost:
  - distribution
  - storage (at both large and small scales)
  - safety
- Safety

“Low-Carbon” Electricity

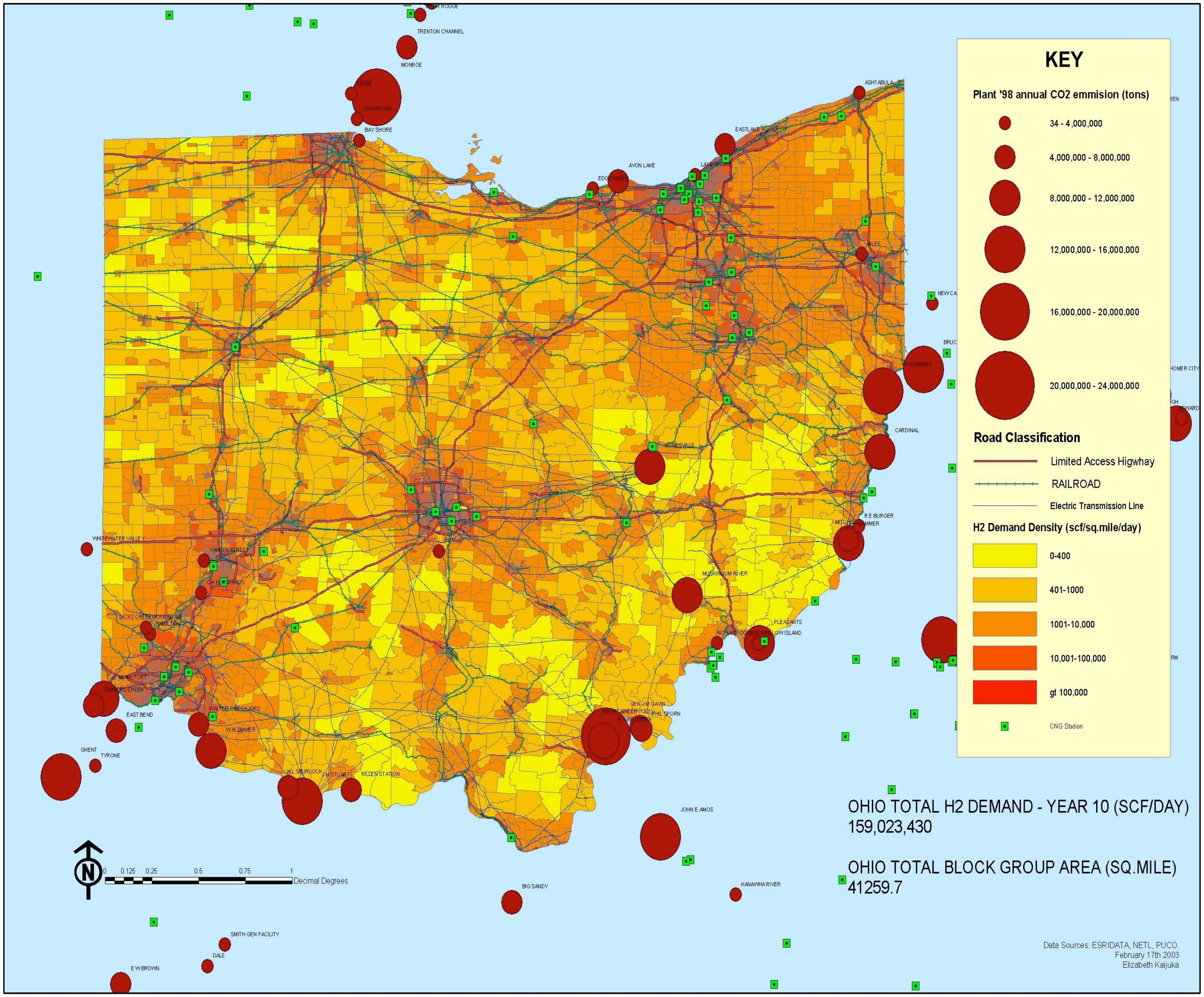
- Electricity grid already exists.
- Competition between:
  - “Decarbonized” fossil-based, central station power generation, via CO_2 capture and storage (*CCS*),
  - Nuclear power
  - Renewable energy (wind, solar, biomass)

Economics of Base Case System





CASE STUDY - OHIO
YEAR 10 HYDROGEN DEMAND

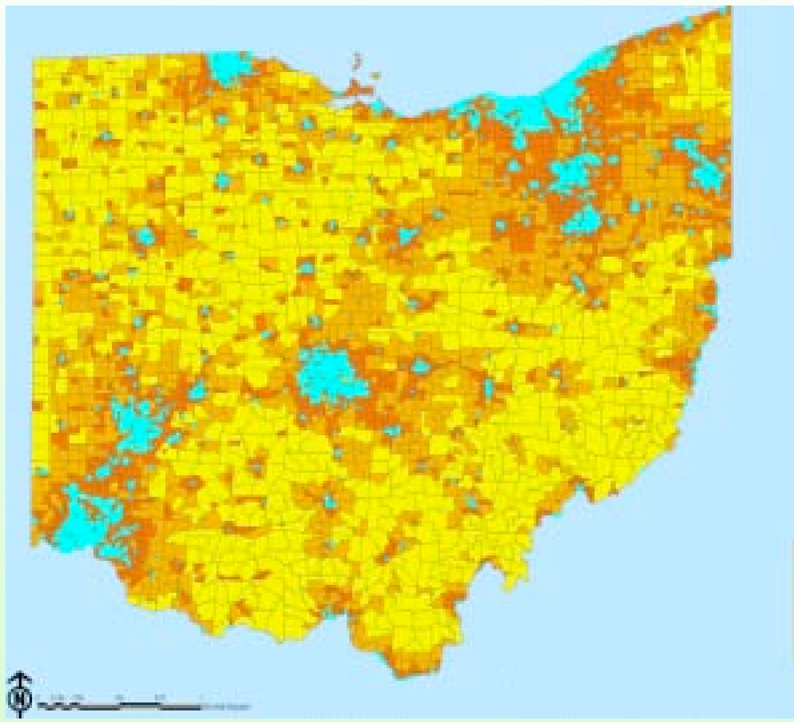


H_2 DEMAND DENSITY (kg/d/km^2): YEAR 1: 25% OF NEW Light Duty Vehicles = H_2 FCVs

Blue shows good locations for refueling station

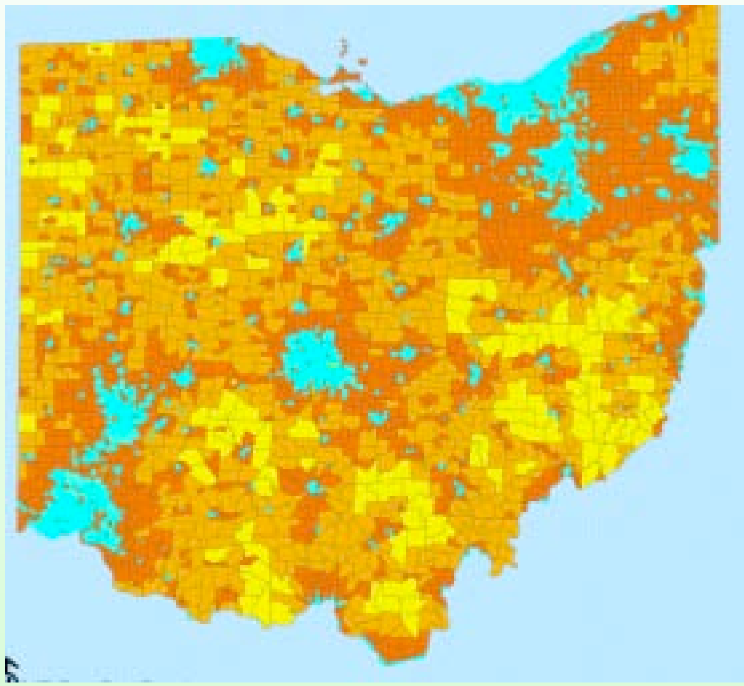
H_2 DEMAND DENSITY ($kg/d/km^2$):

YEAR 5: 25% OF NEW LDVs = H_2 fueled



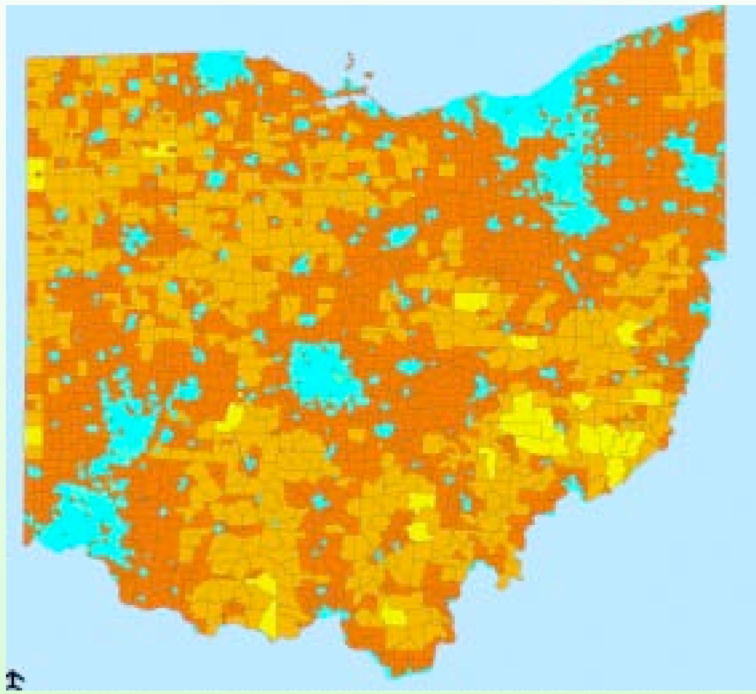
H_2 DEMAND DENSITY (kg/d/km^2):

YEAR 10: 25% OF NEW LDVs = H_2 fueled

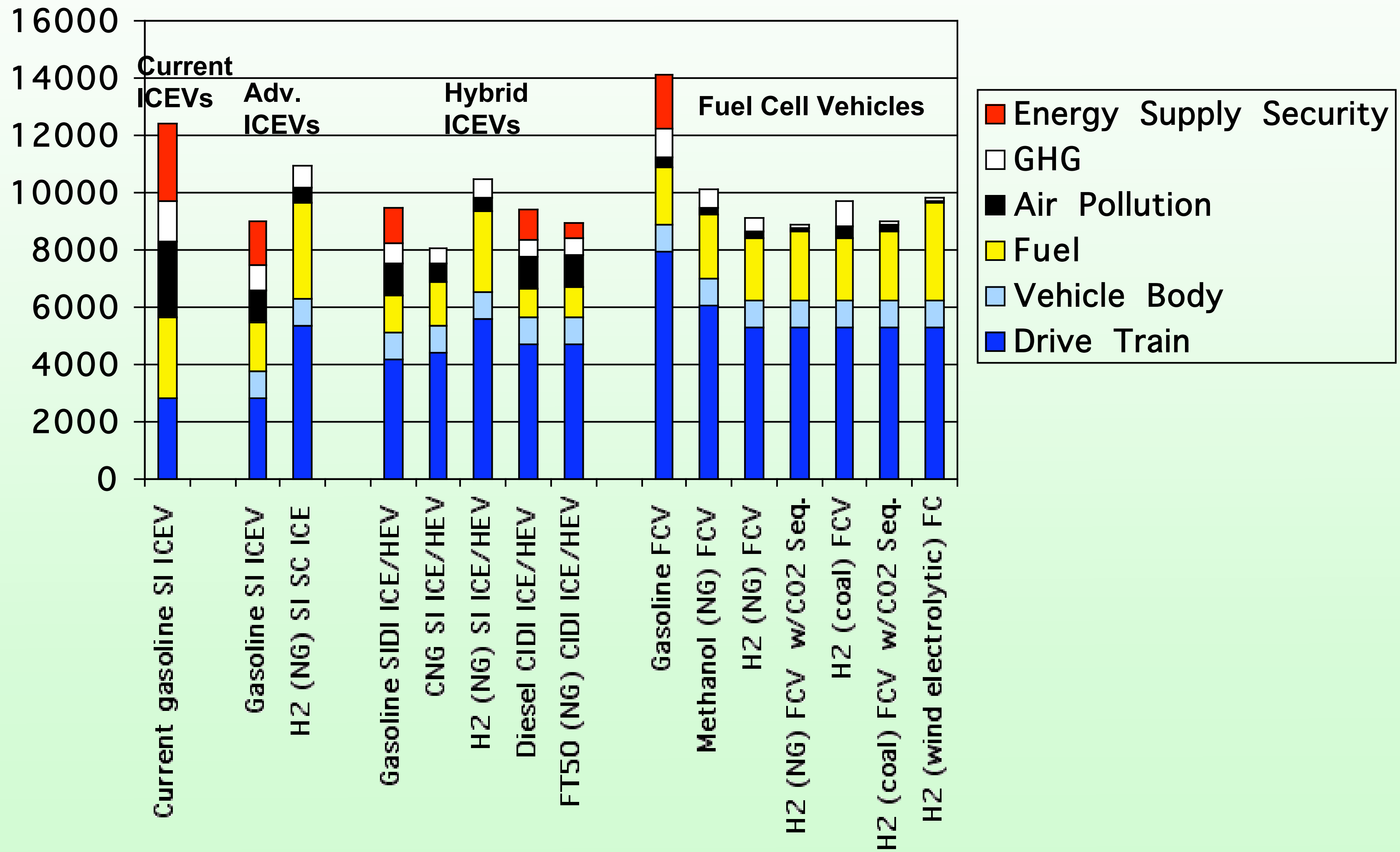


H_2 DEMAND DENSITY ($kg/d/km^2$):

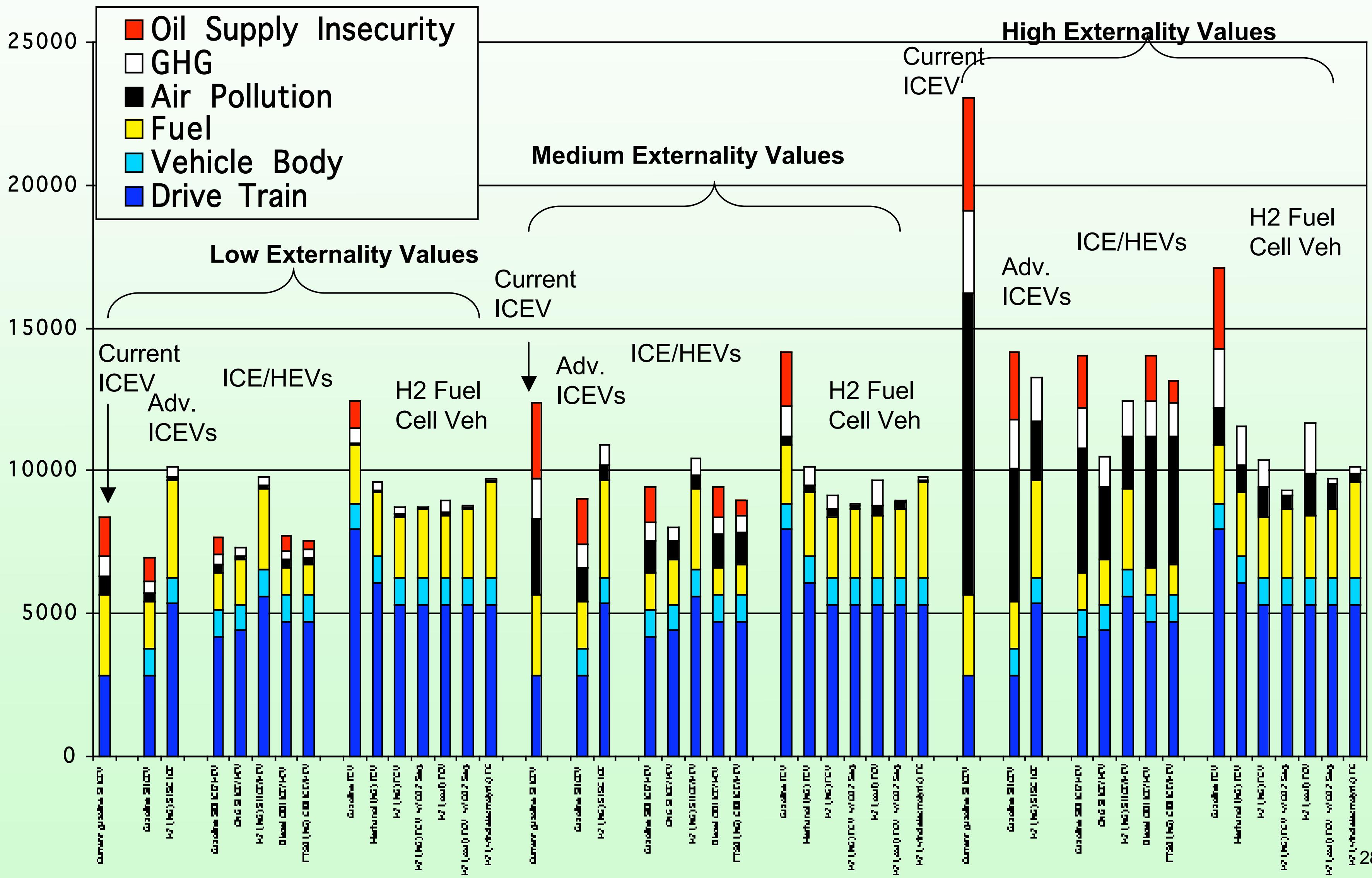
YEAR 15: 25% OF NEW LDVs = H_2 fueled



Societal Lifecycle Costs ($/veh) for Alternative Fueled Vehicles, Including Externality Costs



Societal Lifecycle Costs ($/veh) with Low, Medium, and High Externality Values



The Case for Hydrogen

1. Most of the century's fossil fuel carbon must be captured.
2. About half of fossil carbon, today, is distributed to small users – buildings, vehicles, small factories.
3. The costs of retrieval, once dispersed, will be prohibitive.
4. An all-electric economy is unlikely.
5. An electricity-plus-hydrogen economy is the most likely alternative.
6. Hydrogen from fossil fuels is likely to be cheaper than hydrogen from renewable or nuclear energy for a long time.

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 H_2 from coal
- Sulfur, other criteria pollutants, toxics (e.g, Hg) pose major challenges in H_2/electricity manufacture; gasification facilitates low emissions
- Residual environmental, health, and safety issues of coal mining and other low-quality feedstocks

Why Focus on Coal and Gasification?

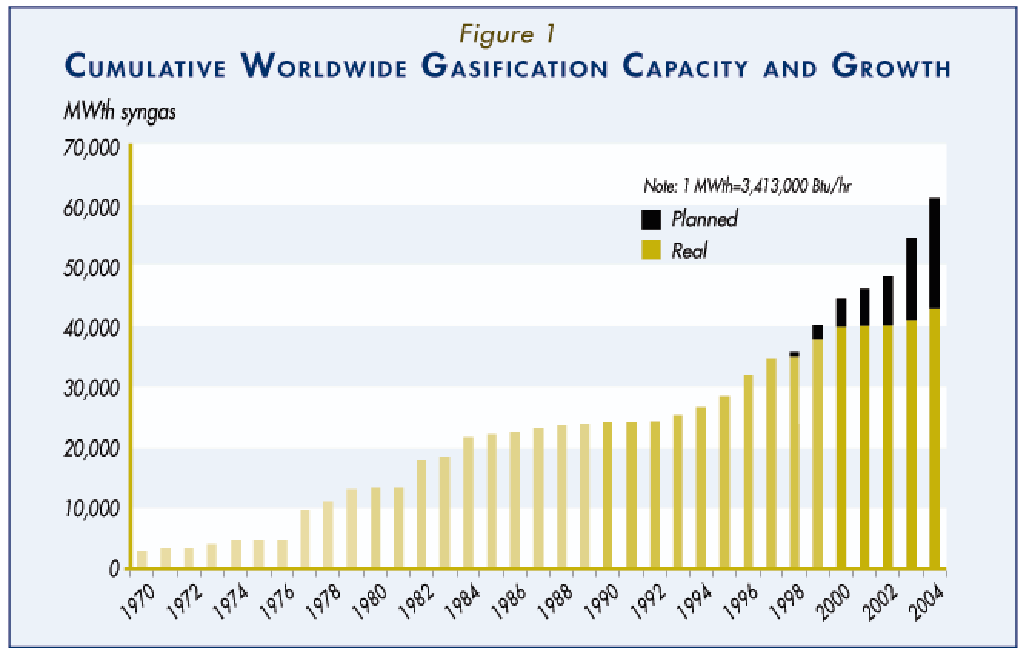
- Coal resources abundant globally.
- Coal prices low and not volatile.
- Much of global population (*e.g., China, India*) heavily coal-dependent.
- Widespread use of coal is a GH disaster.
- Gasification is relatively efficient, and can be quite clean, esp. with *CCS*.
- Gasification provides a route to H2, with its numerous advantages:
  - Secure alternative to oil for transportation
  - near-zero emissions of air pollutants/GHGs

GASIFICATION ACTIVITY WORLDWIDE

- Gasification technology for making chemicals in market by 1970
- Cool Water demonstration of coal IGCC power, 1984-1989

61 GW_{th} cum syngas capacity:

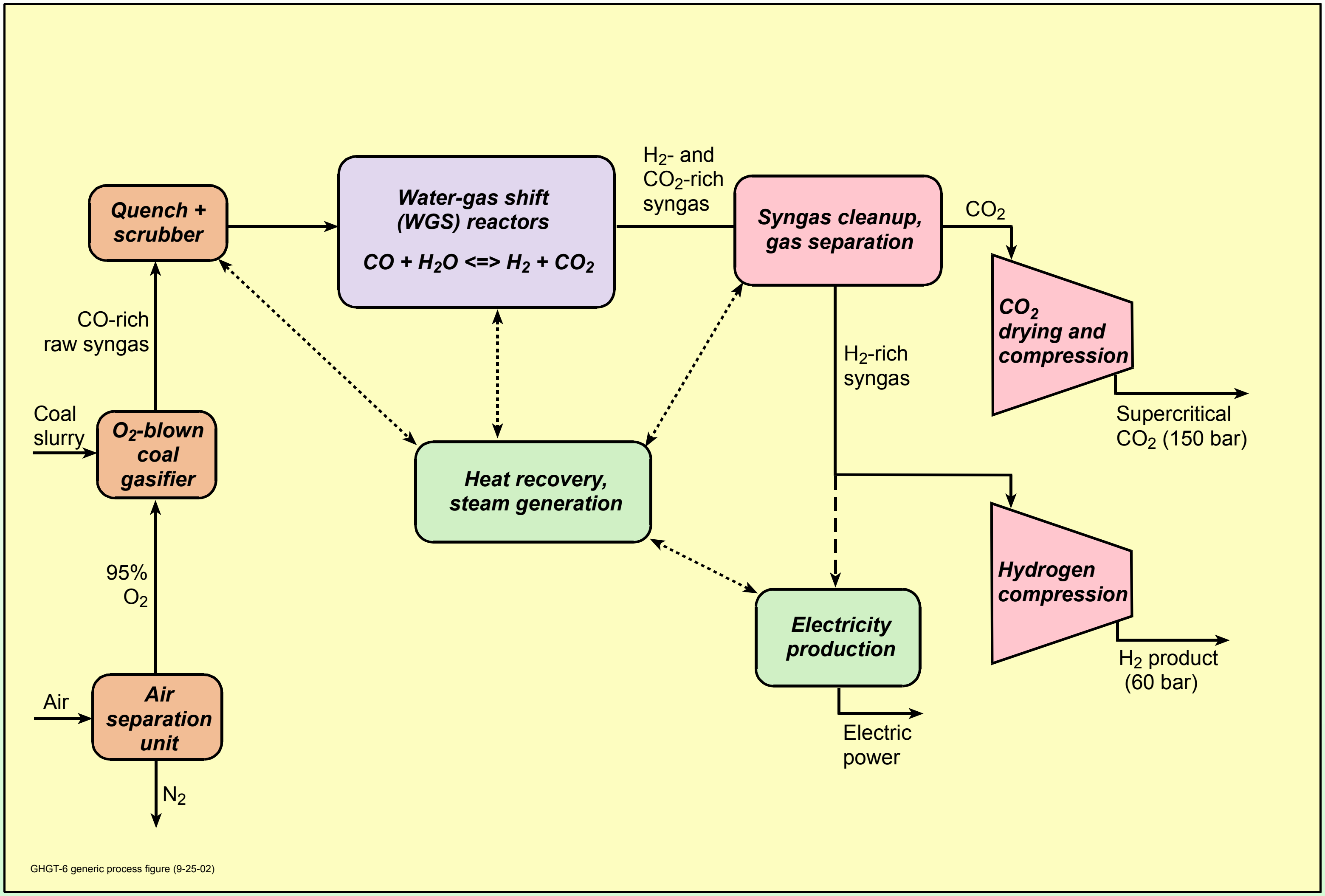
- By activity:
  - 24 GW_{th} chemicals
  - 23 GW_{th} power
  - 14 GW_{th} synfuels
- By region:
  - 19 GW_{th} W Europe
  - 18 GW_{th} Asia/Australia
  - 10 GW_{th} N America
  - 10 GW_{th} Africa/ME
  - 3 GW_{th} E Europe/FSU
  - 1 GW_{th} Latin America
- By feedstock:
  - 27 GW_{th} pet residuals
  - 27 GW_{th} coal
  - 6 GW_{th} NG
  - 1 GW_{th} biomass



Source: SFA Pacific, *Gasification—Worldwide Use and Acceptance*, prepared for the US DOE, January 2000

- New syngas capacity being added @ 3 GW_{th}/y
- Most power at refineries via "polygeneration"
- Coal power growth constrained by NGCC competition

Generic Process: Coal to H_2, Electricity, and CO_2

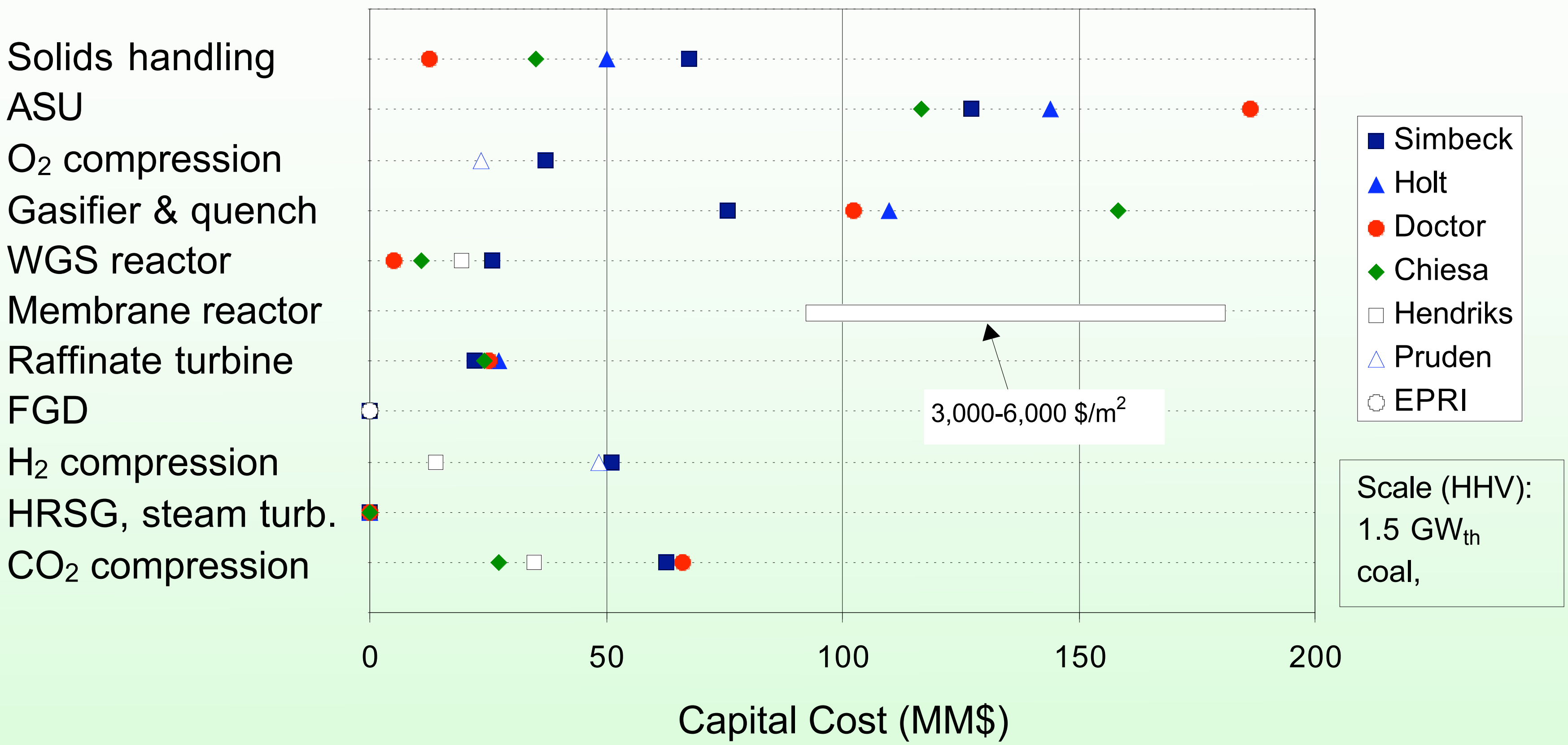


- All work presented here is based on O_2-blown, entrained flow, coal gasification (e.g. Texaco, E-Gas gasifiers).

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 H_2 production systems (both conventional and membrane-based)

Estimates of Overnight Component Capital Costs



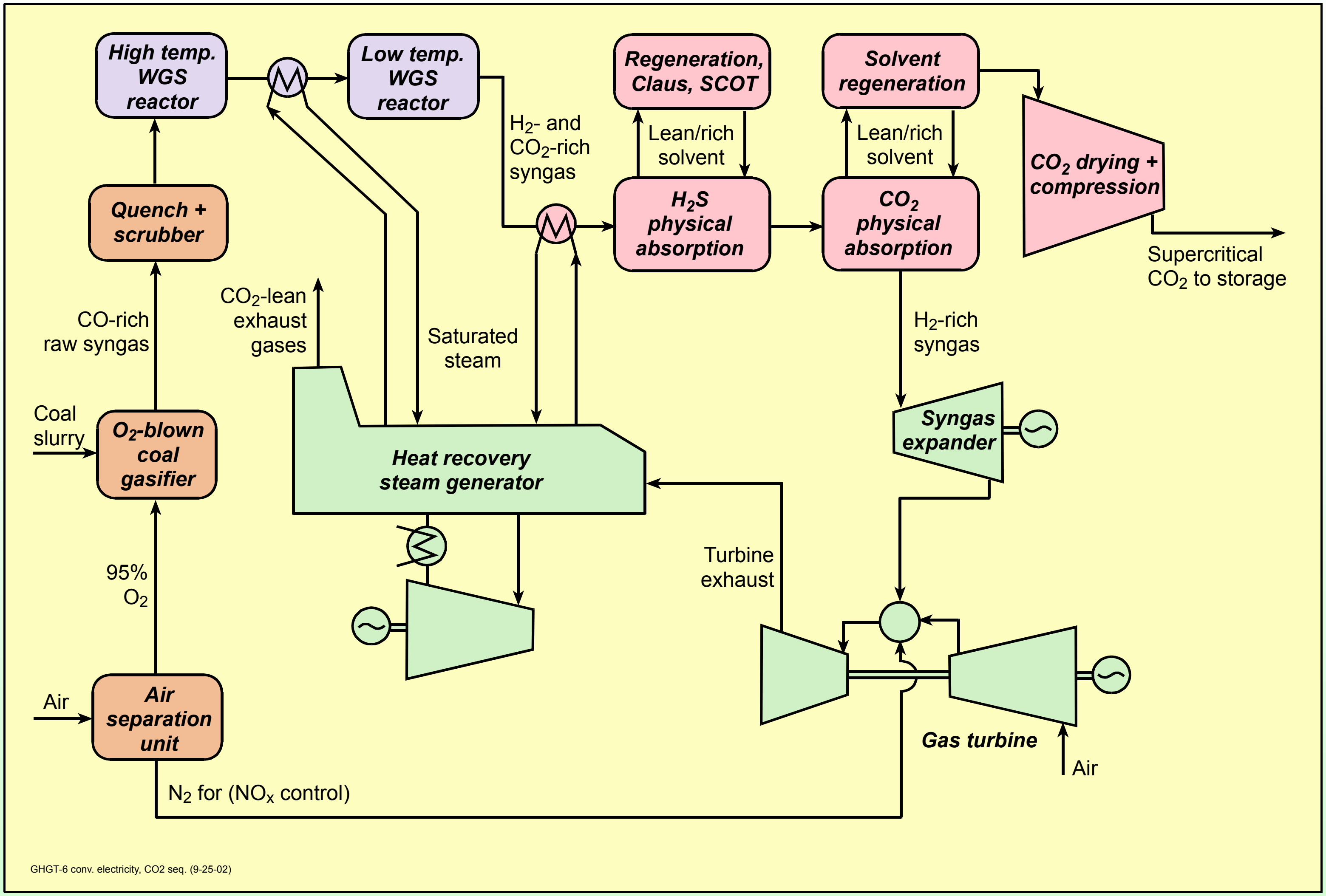
- Significant variation found in cost values, methodology, and depth of detail.
- Our cost model is a self-consistent set of values from the literature.
- Cost database is evolving; less reliable values removed; range is narrowing.
- Uncertainty shown above leads to an uncertainty of ±10-15% in H_2 cost.

Economic Assumptions

Coal price (year 2020 EIA est.)	1.2 $/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)
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	2002
Plant scale	1 GW_{th} H_2

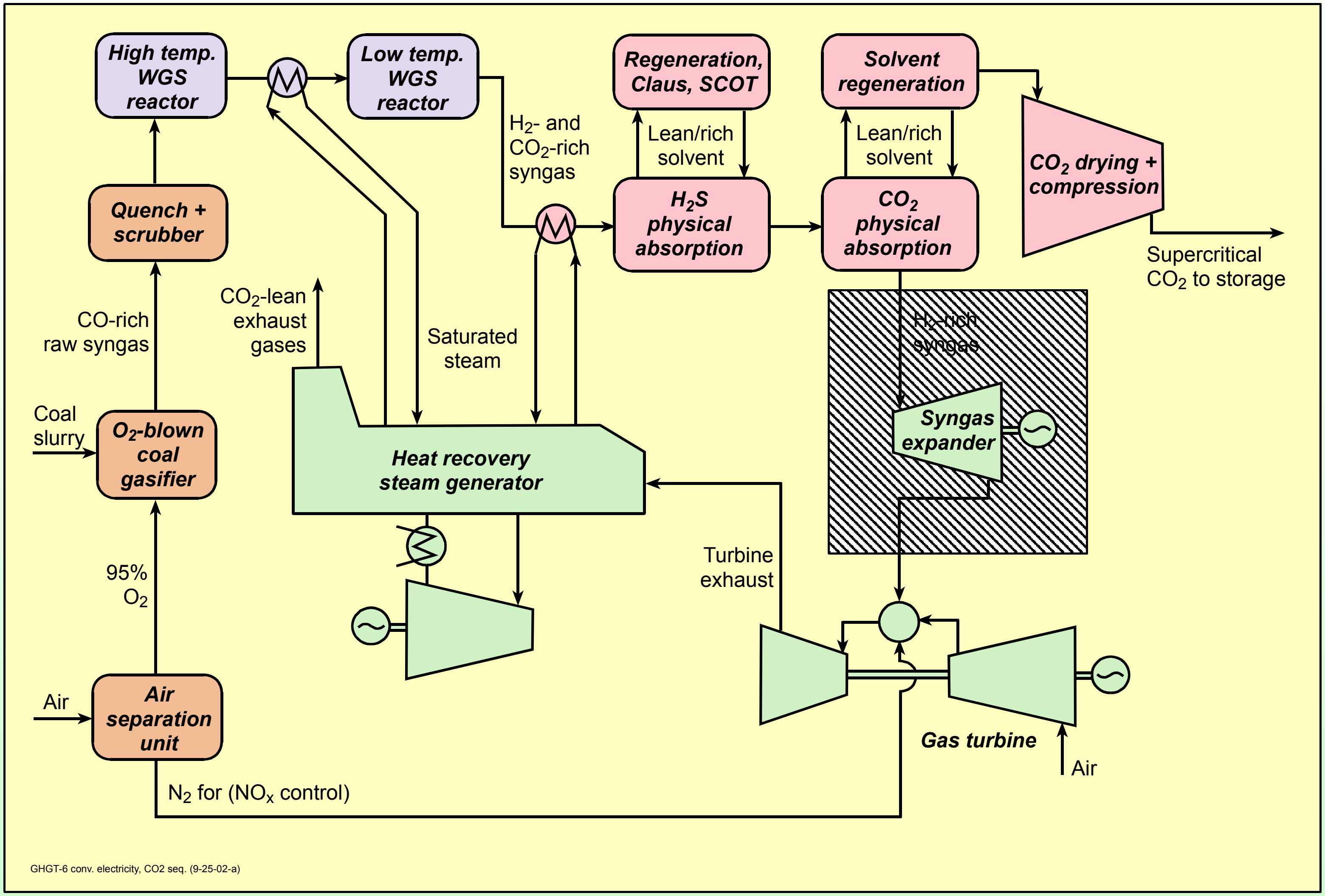
* Assuming a 10% real interest rate

Coal IGCC Electricity with CO_2 Capture



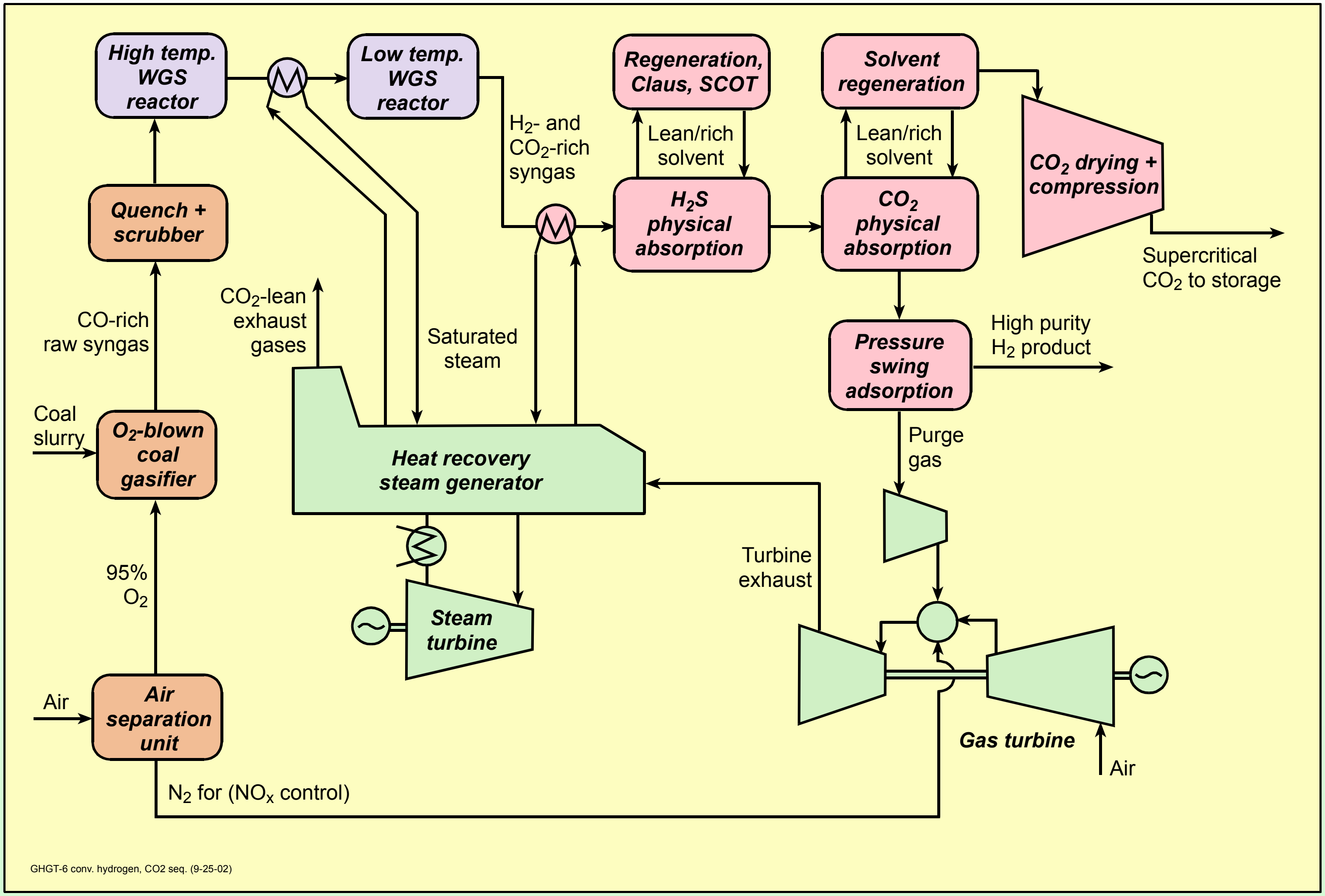
• Plant scale: 362 MW_e, efficiency: 34.9% (HHV), cost: 6.5 ¢/kWh (no carbon tax) vs. 4.8 ¢/kWh venting, 6.7 ¢/kWh (at 96 \$/tonne C). (70 bar gasifier with quench cooling)

H_2 Production: Add H_2 Purification/Separation



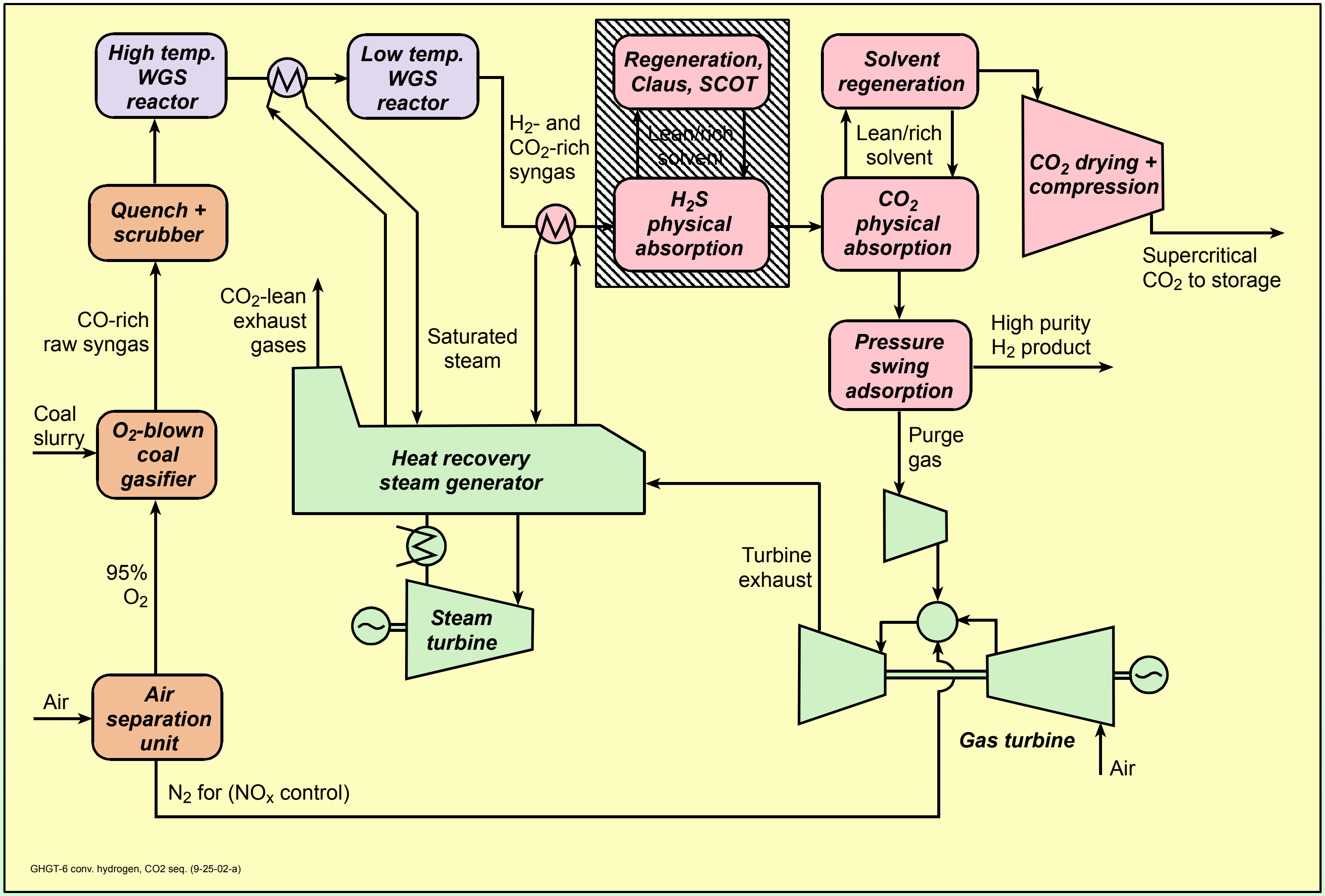
• Replace syngas expander with PSA and purge gas compressor.

Conventional H_2 Production with CO_2 Capture



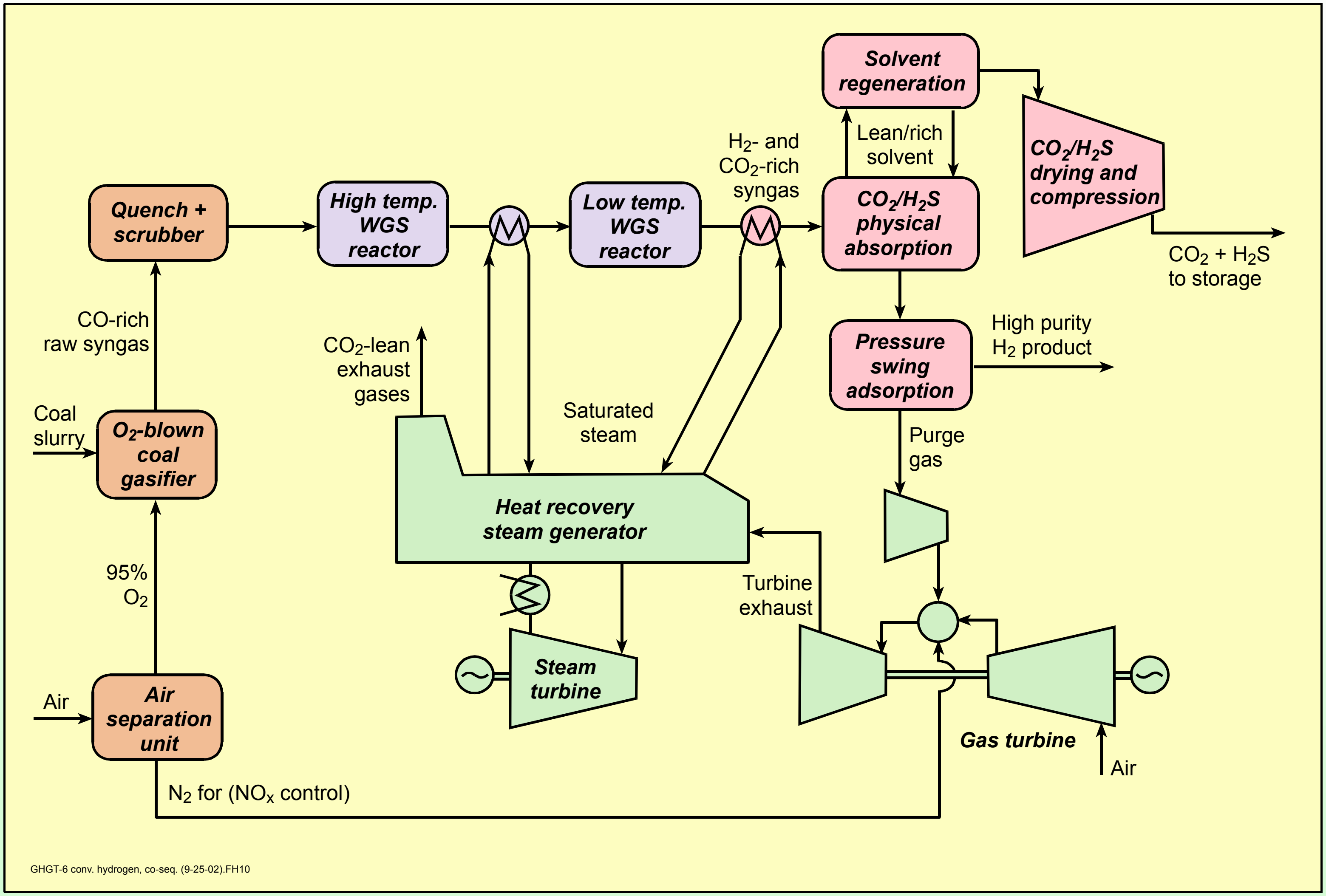
- 1285 MW_{th} H_2 (HHV) + 39 MW electricity, efficiency η^{HHV}=68.4%, 7.4 $/GJ HHV (no carbon tax). [70 bar gasifier with quench cooling]

Capture (and Co-store) H_2S with CO_2



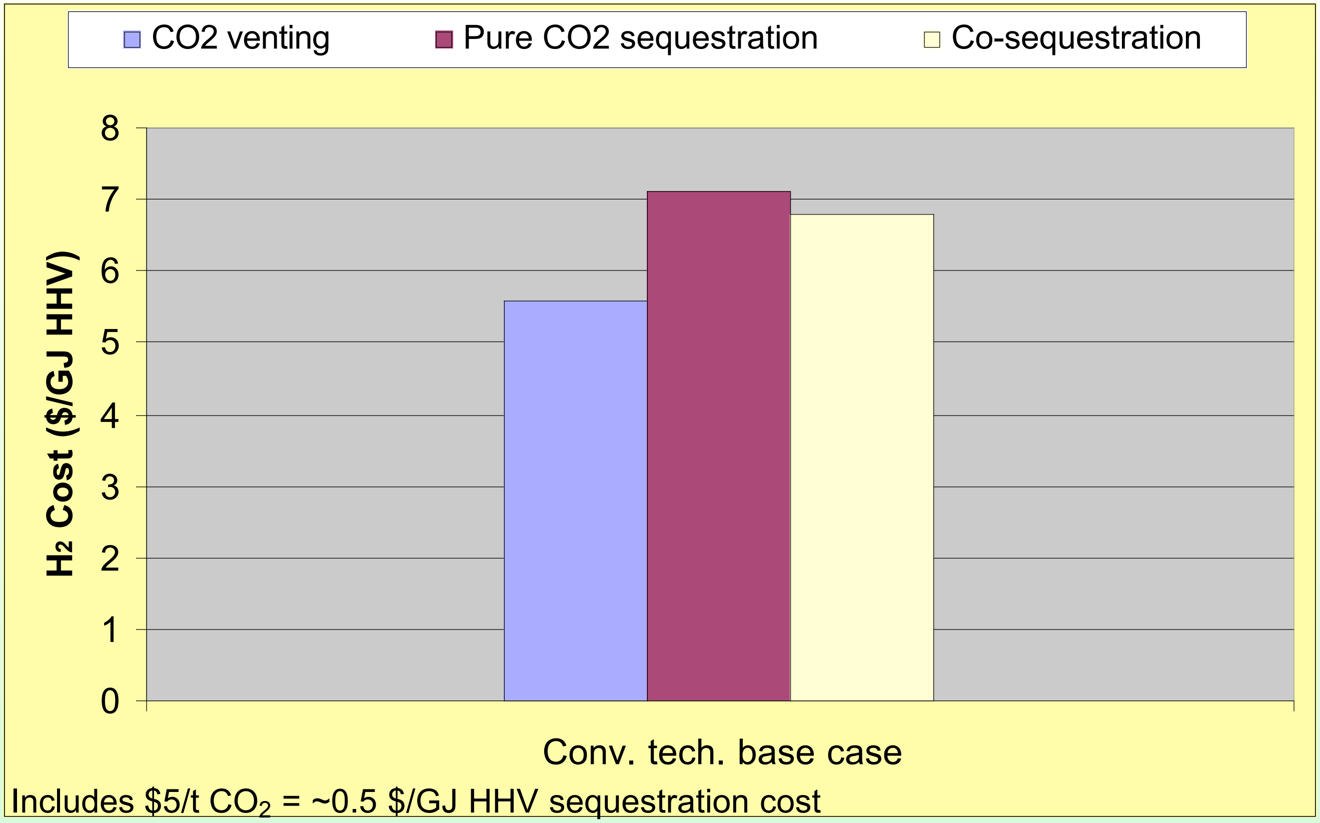
- Remove the traditional acid gas recovery (AGR) unit.

Conventional H_2 Production with CO_2/H_2S Capture



- Resulting system is simpler and cheaper.

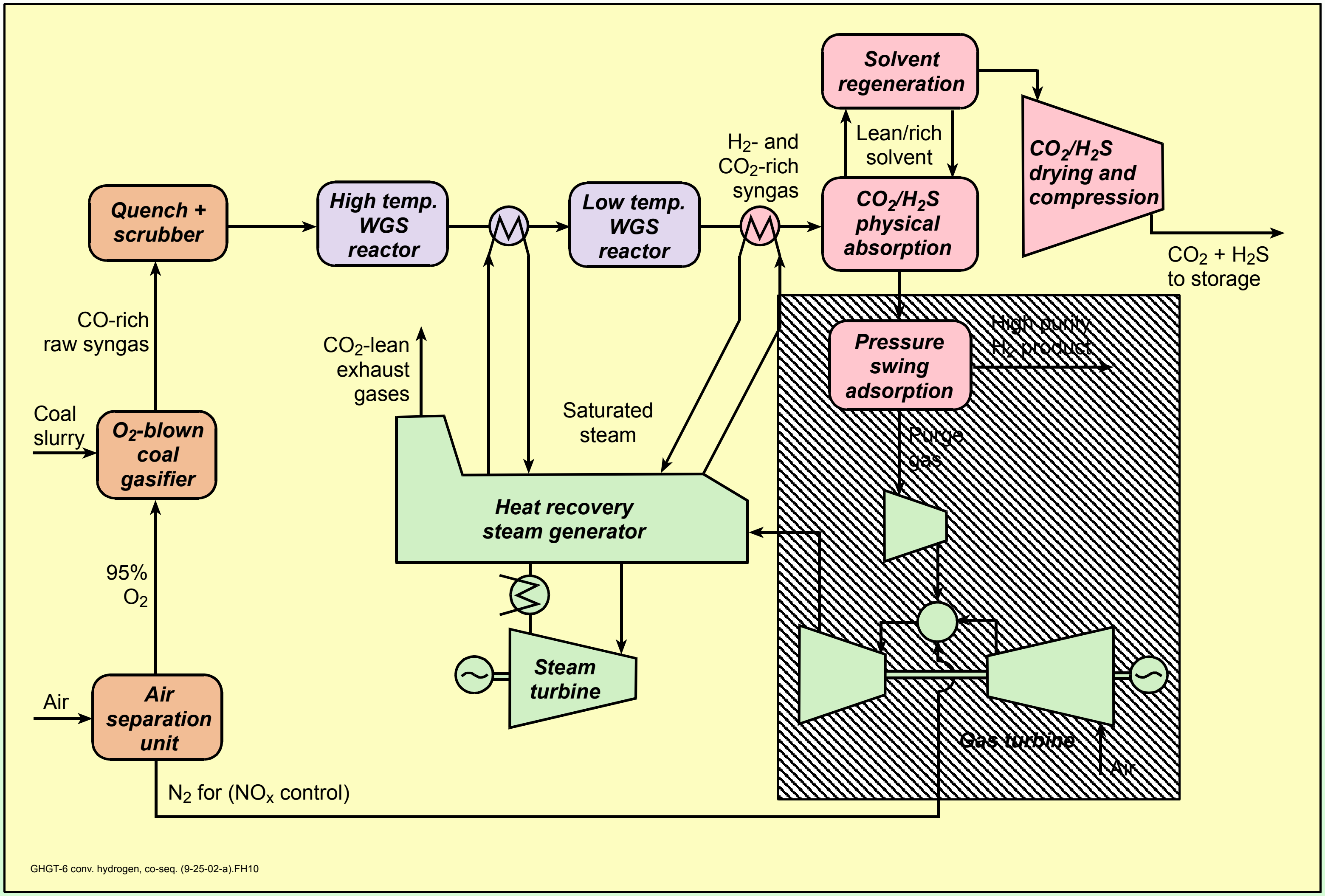
Conventional H_2 with Co-Sequestration of CO_2 and Sulfur-bearing Species



- **CO_2 capture and sequestration lowers efficiency by ~3% and increases H_2 cost by ~ 1.5 $/GJ.**

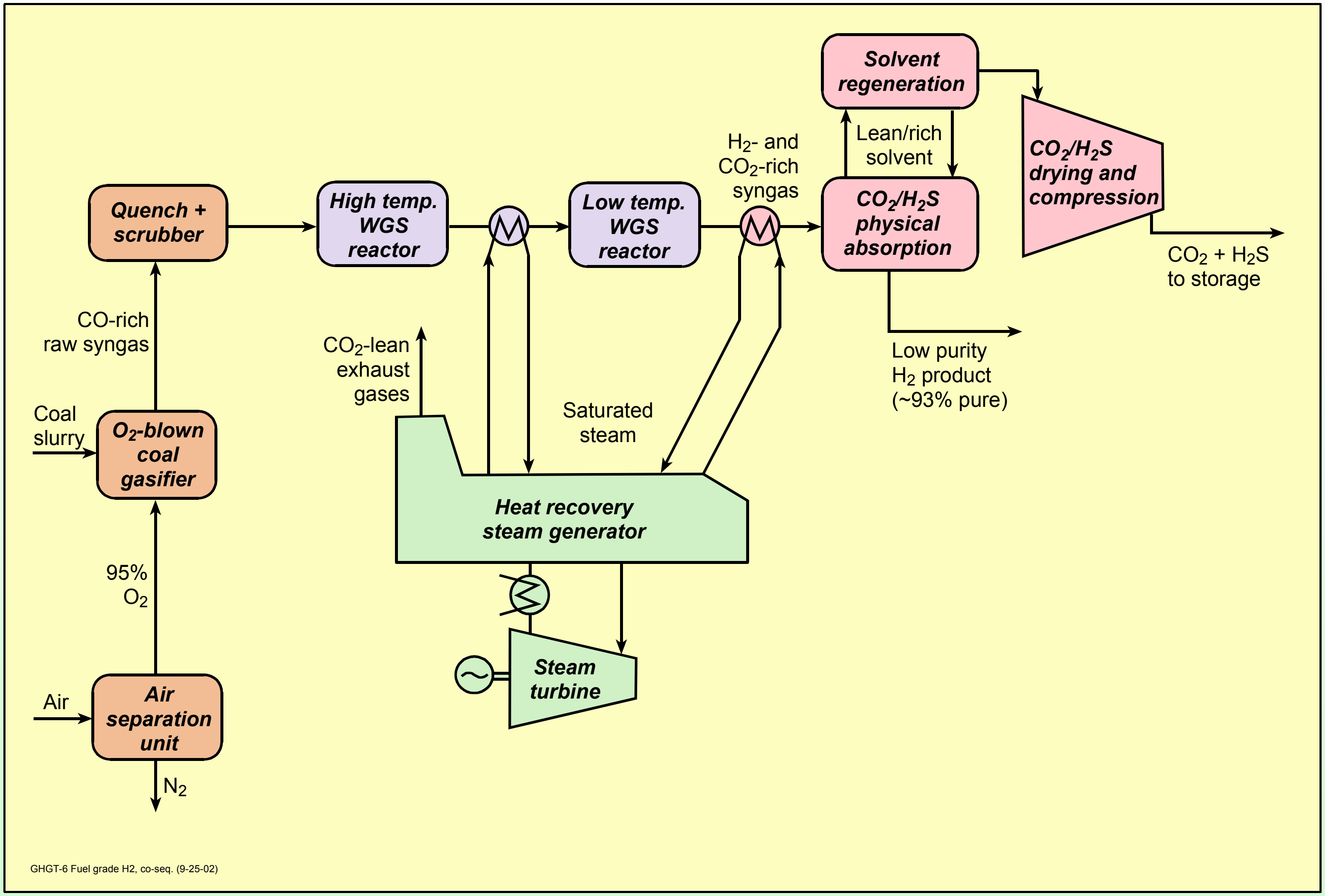
  (Cost of CO_2 pipeline transport and disposal used here is 0.4-0.6 $/GJ.)
- **Co-sequestration has potential to lower H_2 cost by 0.25-0.75 $/GJ, depending on sulfur content of coal.**

Produce "Fuel Grade" H_2 with CO_2/H_2S Capture



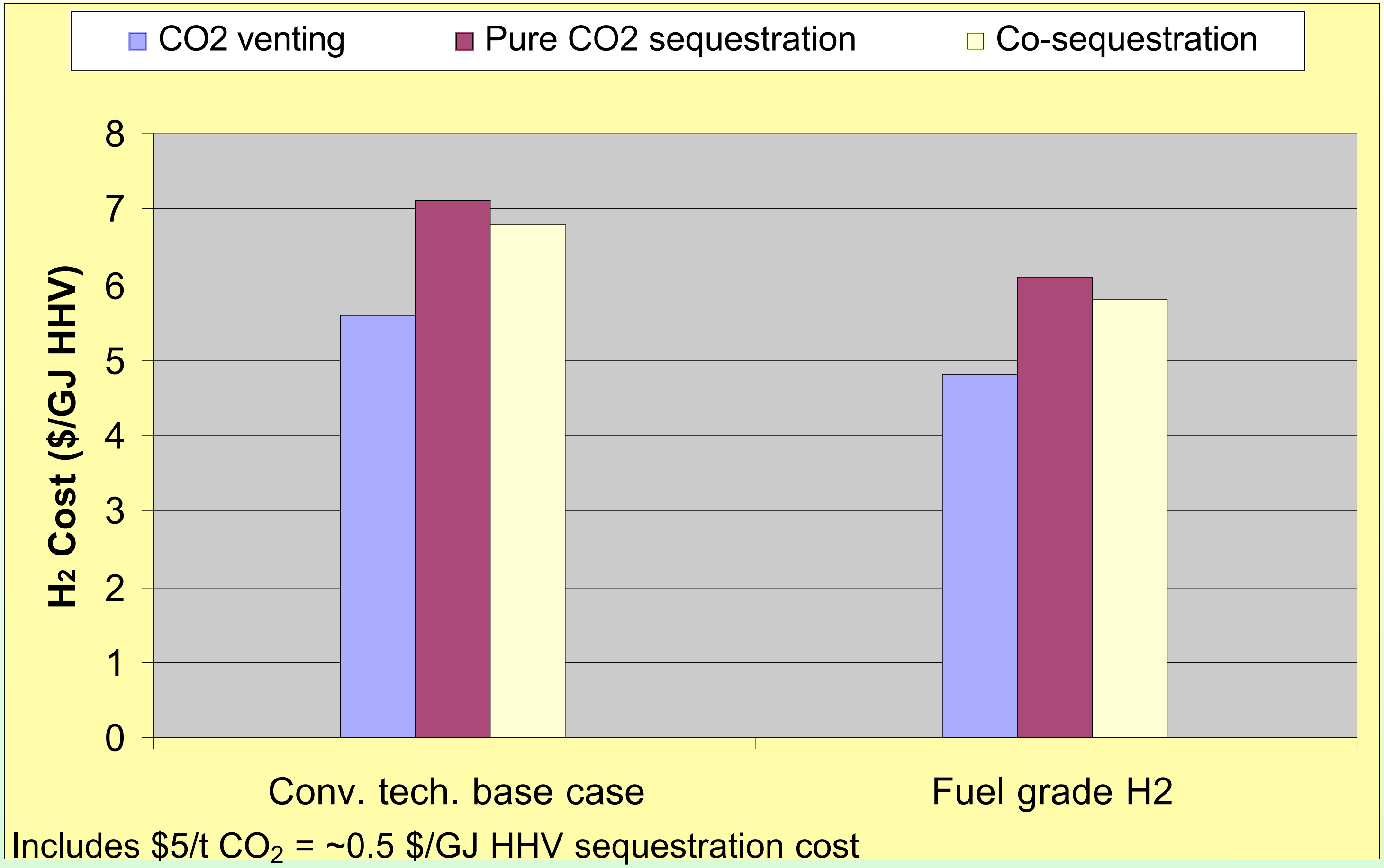
• Remove the PSA and gas turbine; smaller steam cycle.

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



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

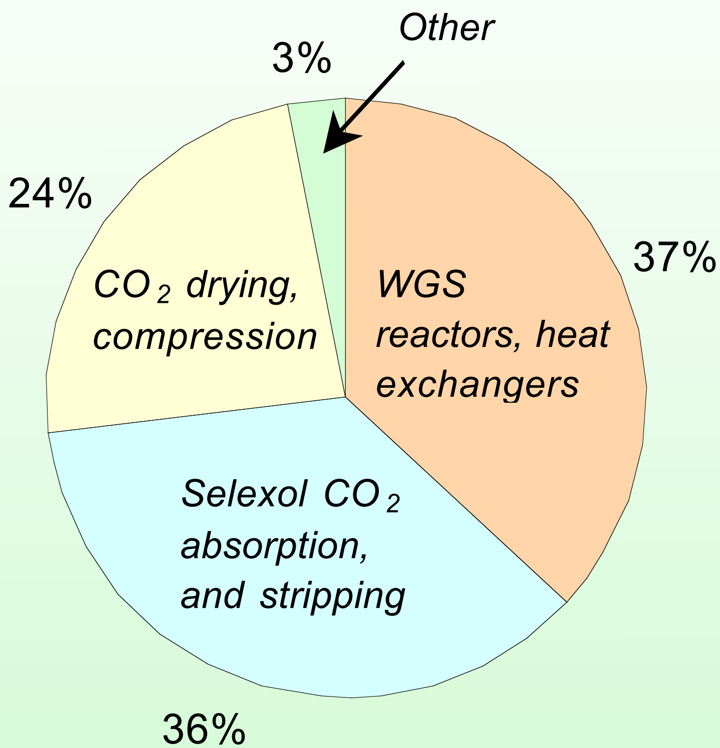
Production of “Fuel Grade” H_2



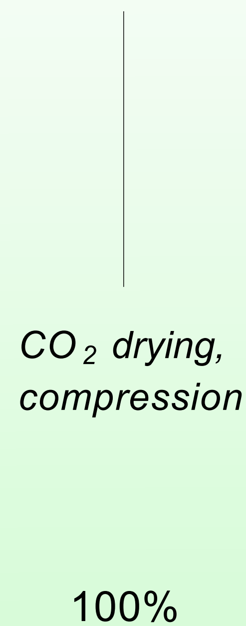
- Reduced H_2 purity yields a significant cost savings: 1.0-1.4 $/GJ.
- Fuel grade H_2 will be more competitive with gas and oil in the heating sector, and might be adequate for transportation (H_2 ICEVs; barrier to PEM FCEVs?)

Breakdown of Incremental Capital Cost for CO_2 Capture

Coal IGCC
(1326 → 1737 $/kW$_e$)

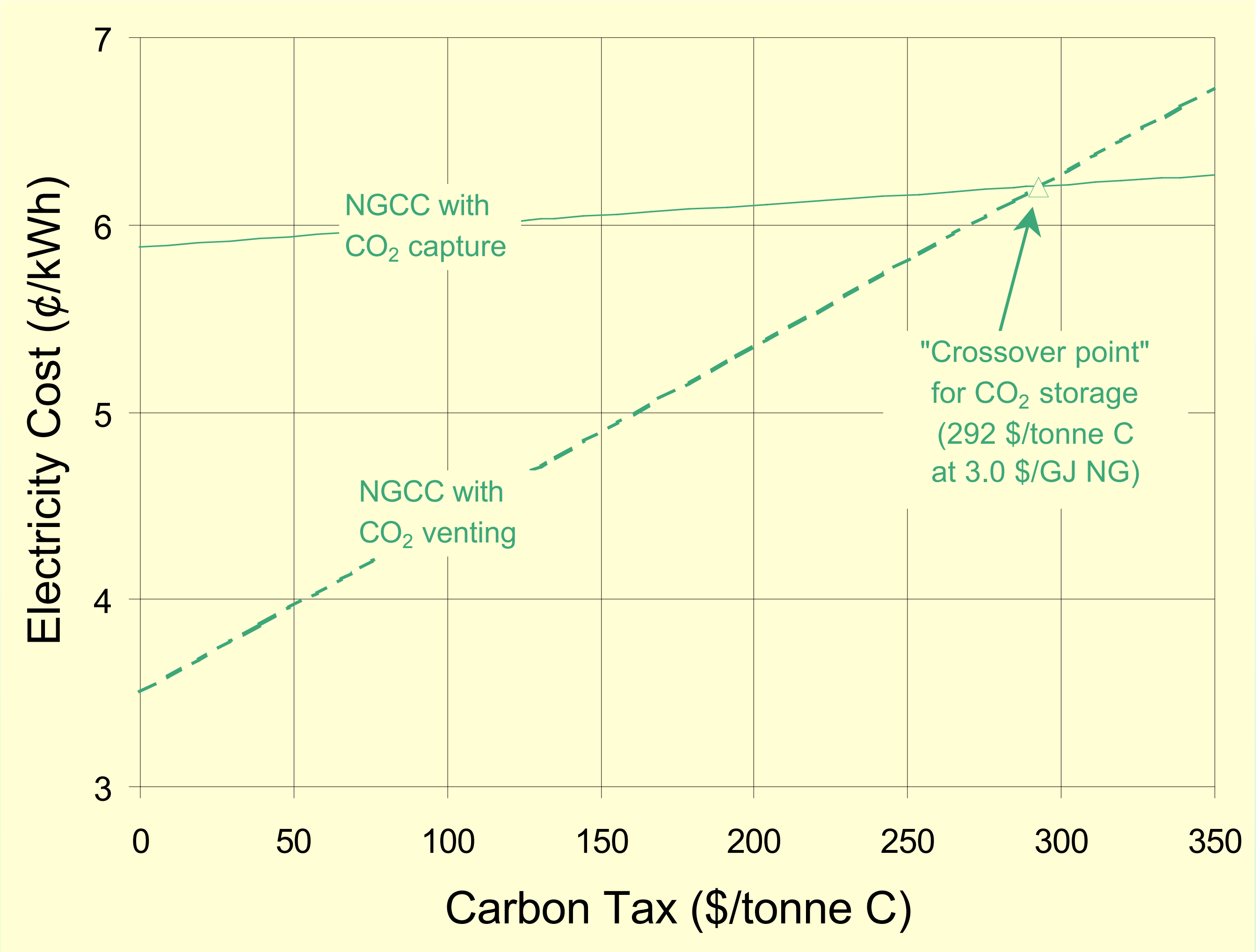


H_2 from Coal
(706 → 742 $/kW$_{th}$ H_2 HHV)



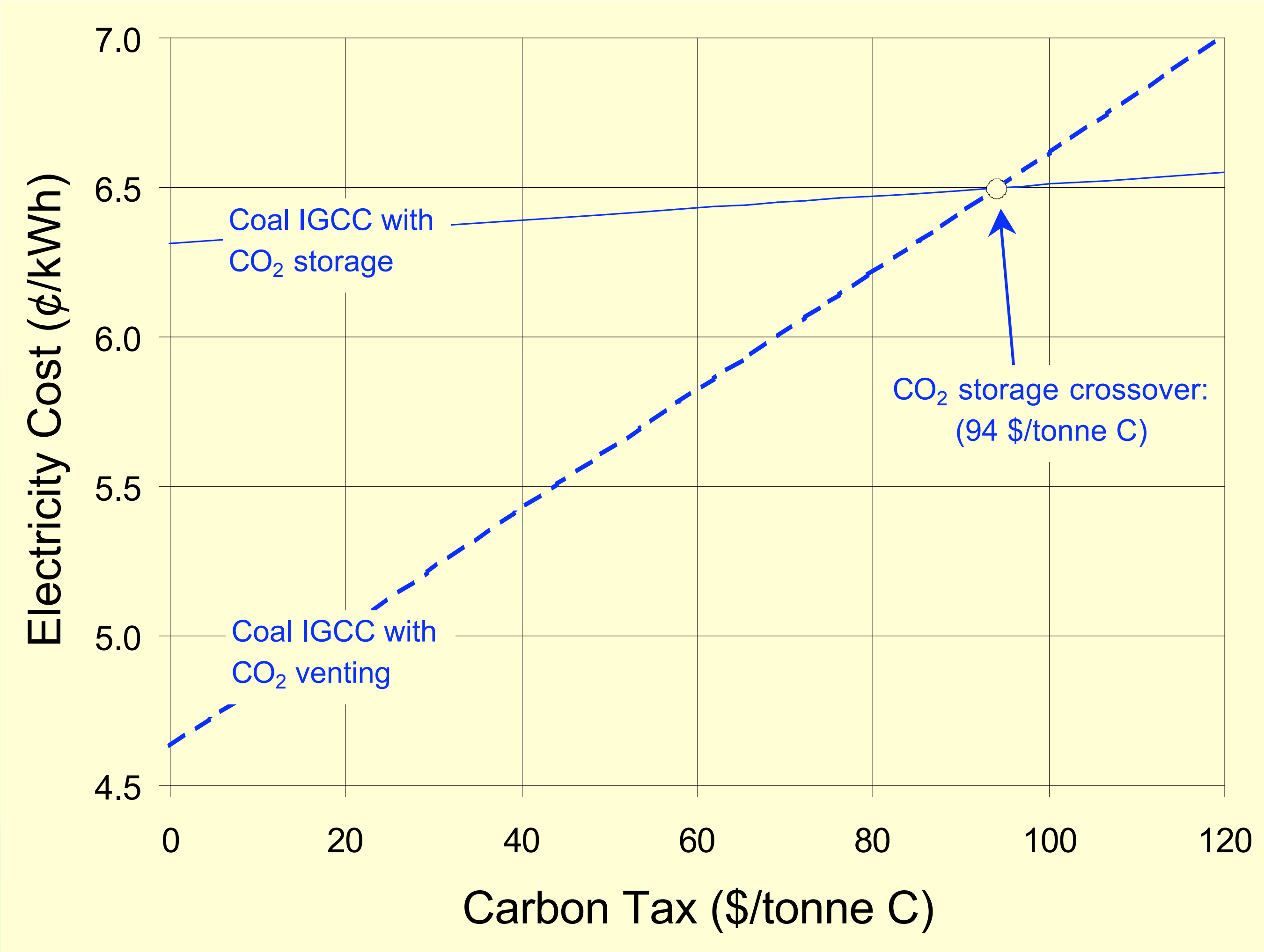
- Incremental cost for CO_2 capture is less for hydrogen than electricity because much of the equipment is already needed for a H_2 plant.

Economics of NGCC with Carbon Storage



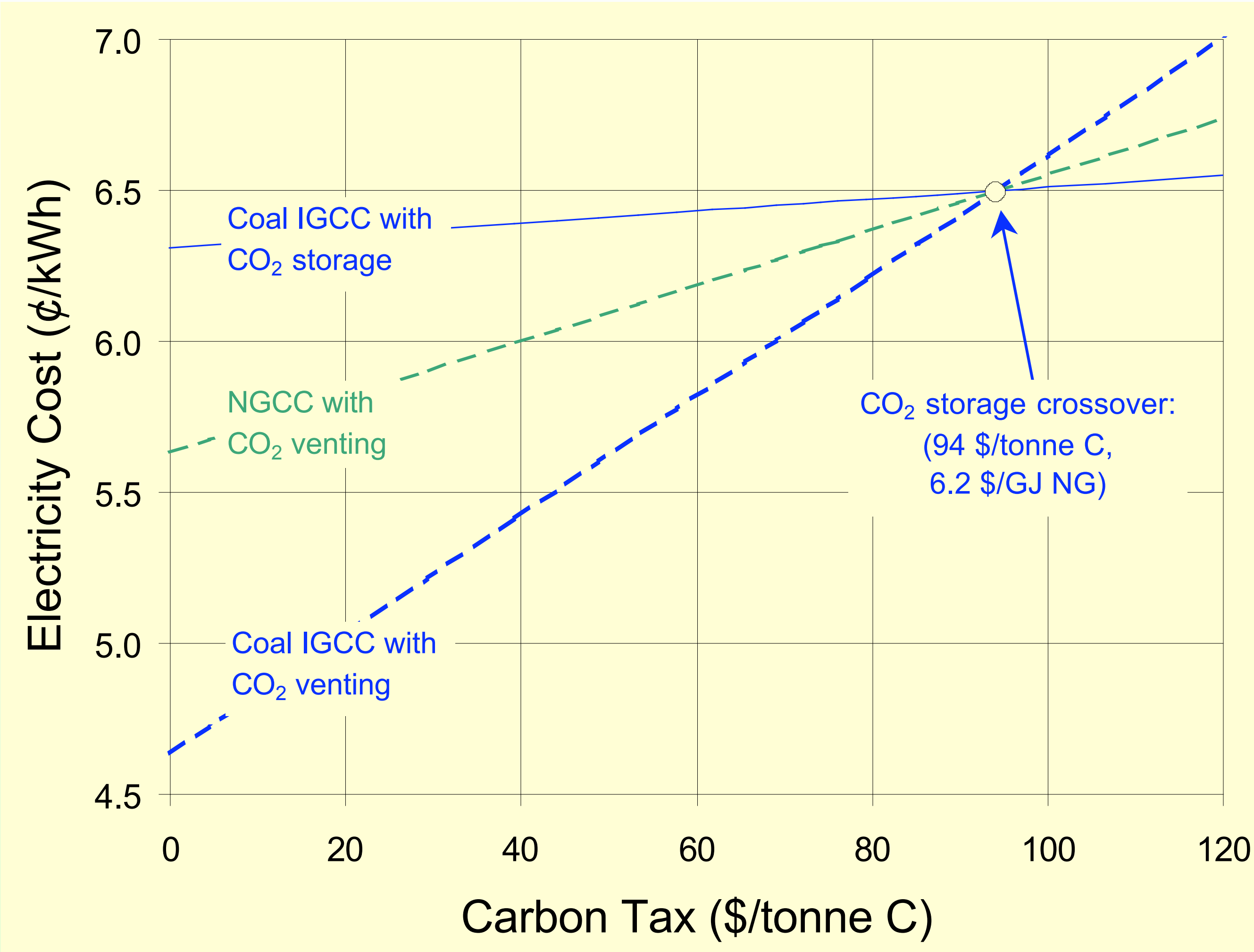
- Carbon tax needed to induce CO_2 storage is extremely high.
- NGCC with CO_2 capture is not considered further.

Economics of Coal IGCC with Carbon Storage



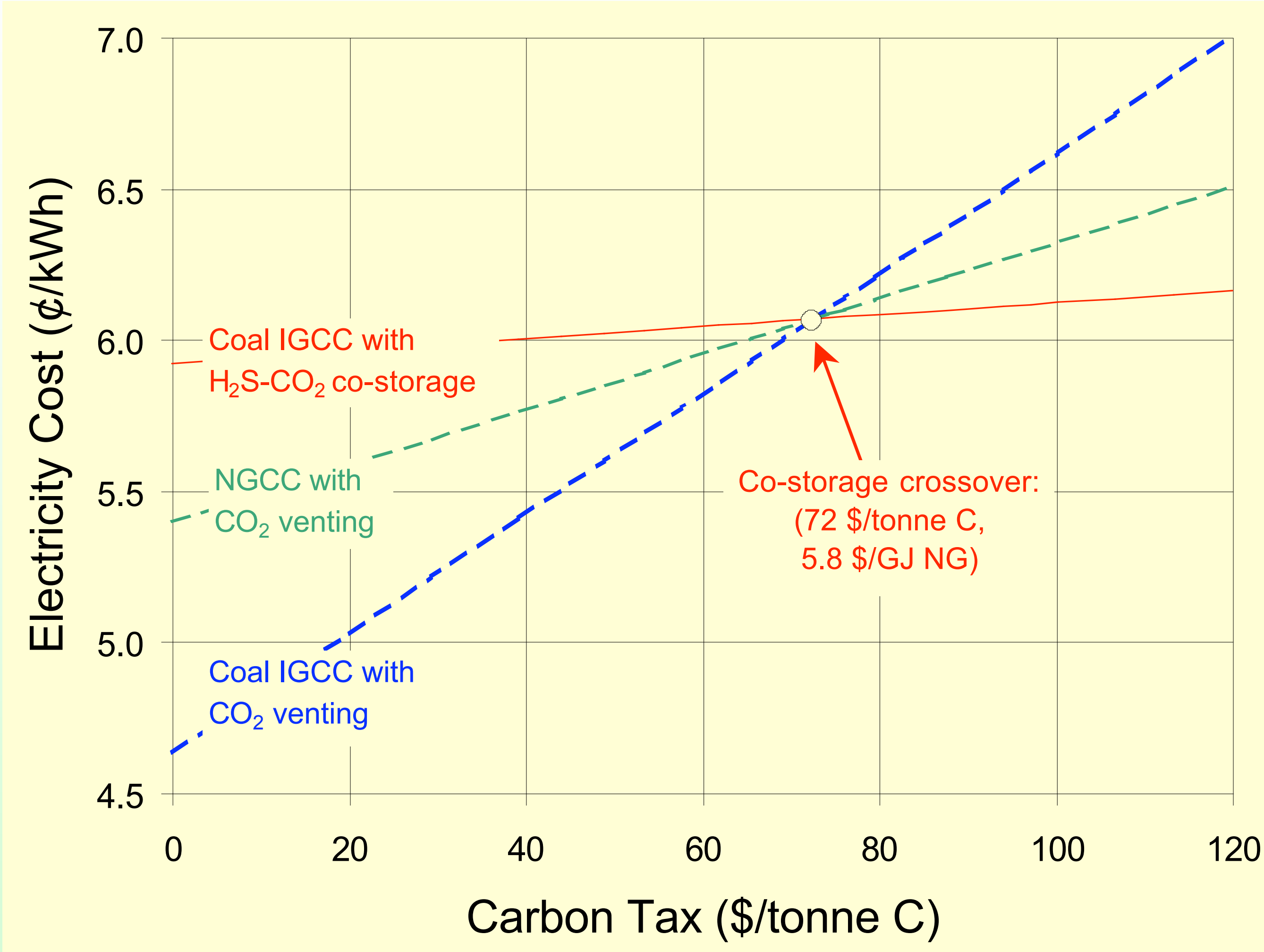
- Tax needed to induce CO_2 storage in coal IGCC is *much* lower than NGCC.
- But, how does coal IGCC+CO_2 storage compete with NGCC+CO_2 venting...

The "Breakeven NG Price" to Induce CO_2 Storage



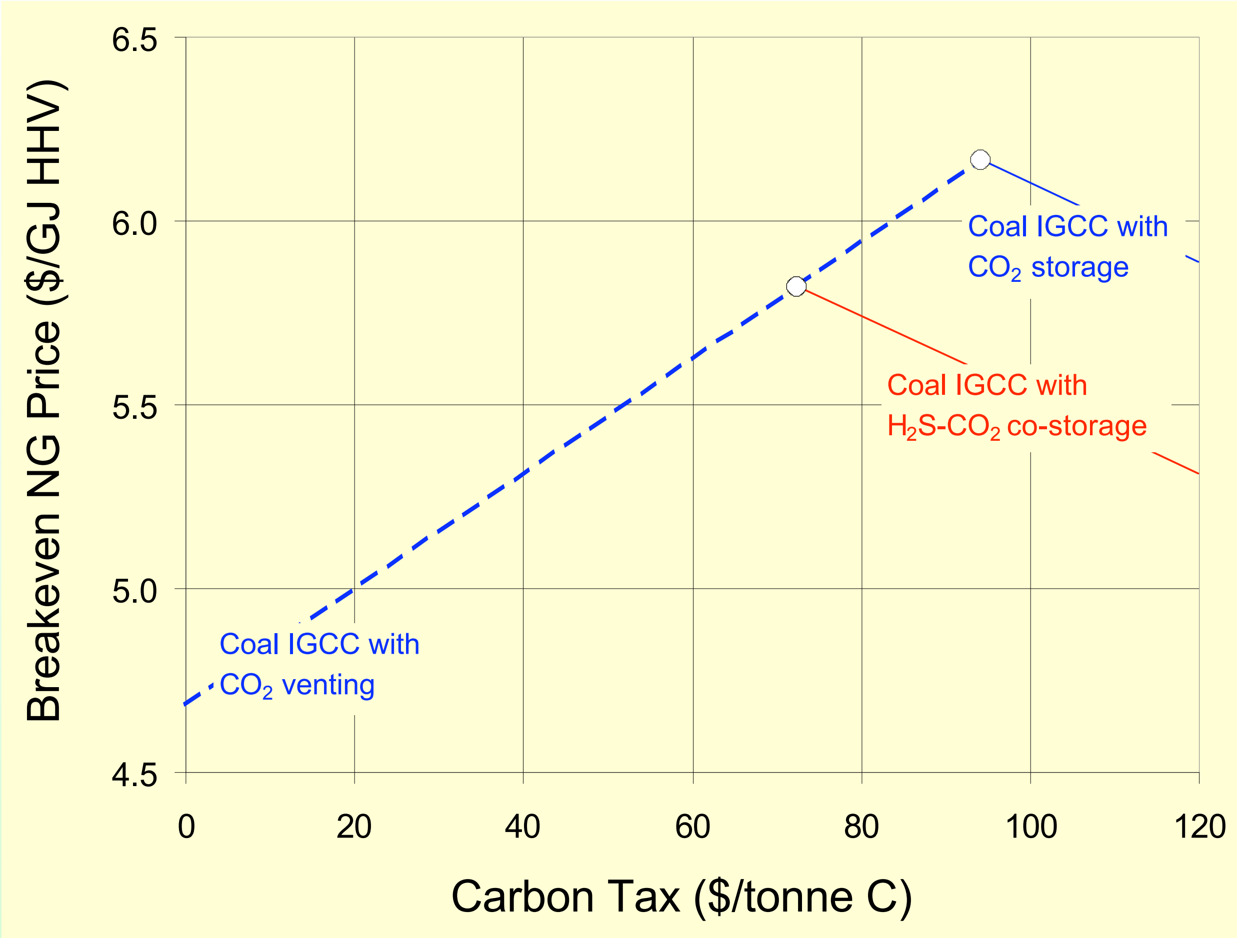
- In addition to the carbon tax, the NG price must exceed ~6 $/GJ for coal IGCC+$CO_2$ storage (...for *any* electricity+CO_2 storage) to be economical!

The Economics of H_2S-CO_2 Co-Storage



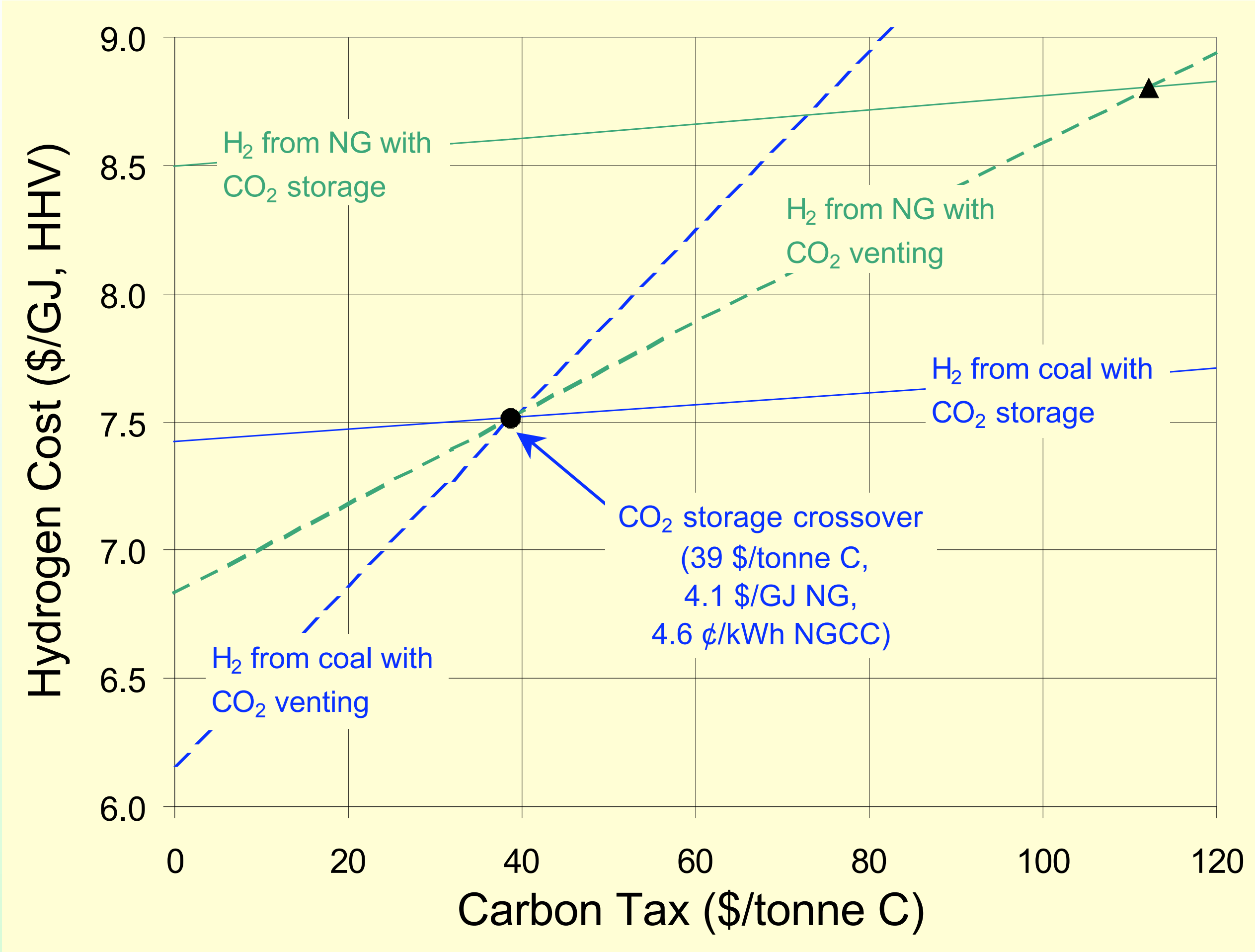
- Co-storage reduces both the crossover carbon tax and breakeven NG price somewhat, but the barrier to carbon storage remains quite high.

Breakeven NG Prices vs. Carbon Tax



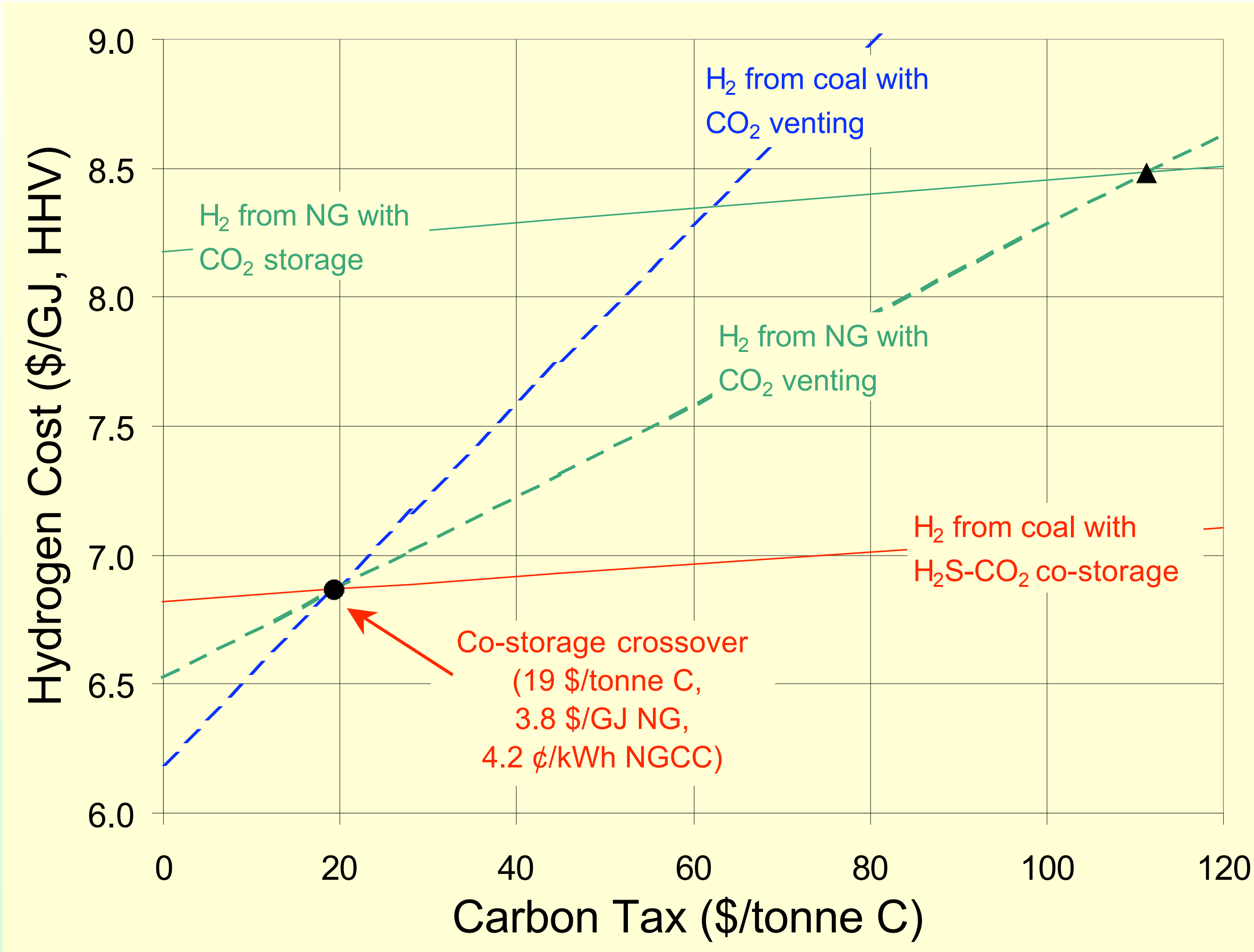
- Without CO_2 storage, coal IGCC competes with NGCC at NG~4.5 $/GJ; the breakeven NG price rises with carbon tax due to coal's high C content.
- Above the crossover tax, CO_2 storage plants out-compete CO_2 venting plants.

Economics of H_2 from Coal with Carbon Storage



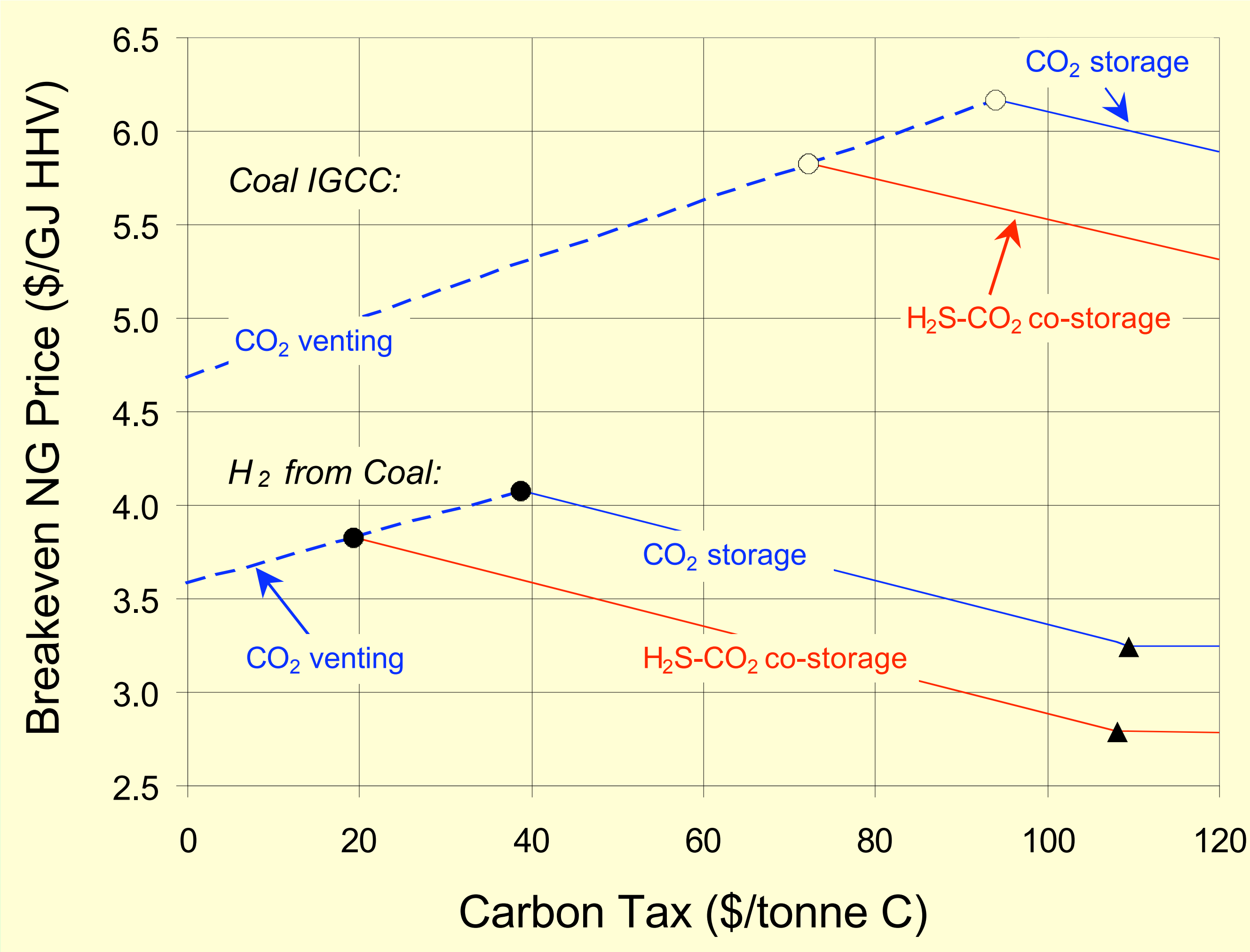
- Both the carbon tax and breakeven NG price needed to induce coal H_2 with CO_2 storage are *much* lower than those for electric power.
- Industrial H_2 from coal might be the earliest CO_2 storage opportunity.

Economics of H_2 from Coal with H_2S-CO_2 Co-Storage



- H_2S-CO_2 co-storage further reduces both the crossover carbon tax and breakeven NG price.

Breakeven NG Prices vs. Carbon Tax



- Breakeven NG prices for coal H_2 mirror those for IGCC (but are lower).

Conclusions

- If CCS is viable, fossil fuels will probably be used for the production of low-carbon electricity and some H_2. The cost of avoided CO_2 emissions is ~100 $/tonne C (200 $/tonne C with respect to old plants).
- The imposition of a simple carbon tax will NOT induce IGCC electricity with CCS at ~100 $/tonne C; a gas price of ~6 $/GJ HHV is also required. Coal may disappear without a “feebate” scheme or portfolio standard to induce IGCC CCS.
- Low-carbon H_2 may be an early opportunity for CCS, in cases where H_2 distribution costs are small.
- H_2 will be available at IGCC plants with CCS, reasonably near demand centers. The penetration of H_2 into heating and transportation will depend on carbon taxes, public policy, and competition from other low carbon energy carriers.

What is (and is Not) Needed?

- Long term CO_2 storage in saline aquifers needs to be validated with *many*, well instrumented demonstration projects in a variety of geologic formations. A need for regulatory and legal frameworks, and standards for well placement, injection, and monitoring.
- The safety (or lack thereof) of H_2 vehicles need to demonstrated by long term studies of H_2 ICEV and FCEV fleets.
- FutureGen appears to be a good vehicle for testing and demonstrating the H_2 economy in its full extent.