Global Carbon Management and the Role of Hydrogen

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Outline of talk

1. The global carbon as a problem of benefits and costs of avoiding carbon build-up to various levels and at various rates.

2. How hydrogen fits within the problem of global carbon.

3. Some on-going work at Princeton on hydrogen production from fossil fuels and hydrogen distribution.

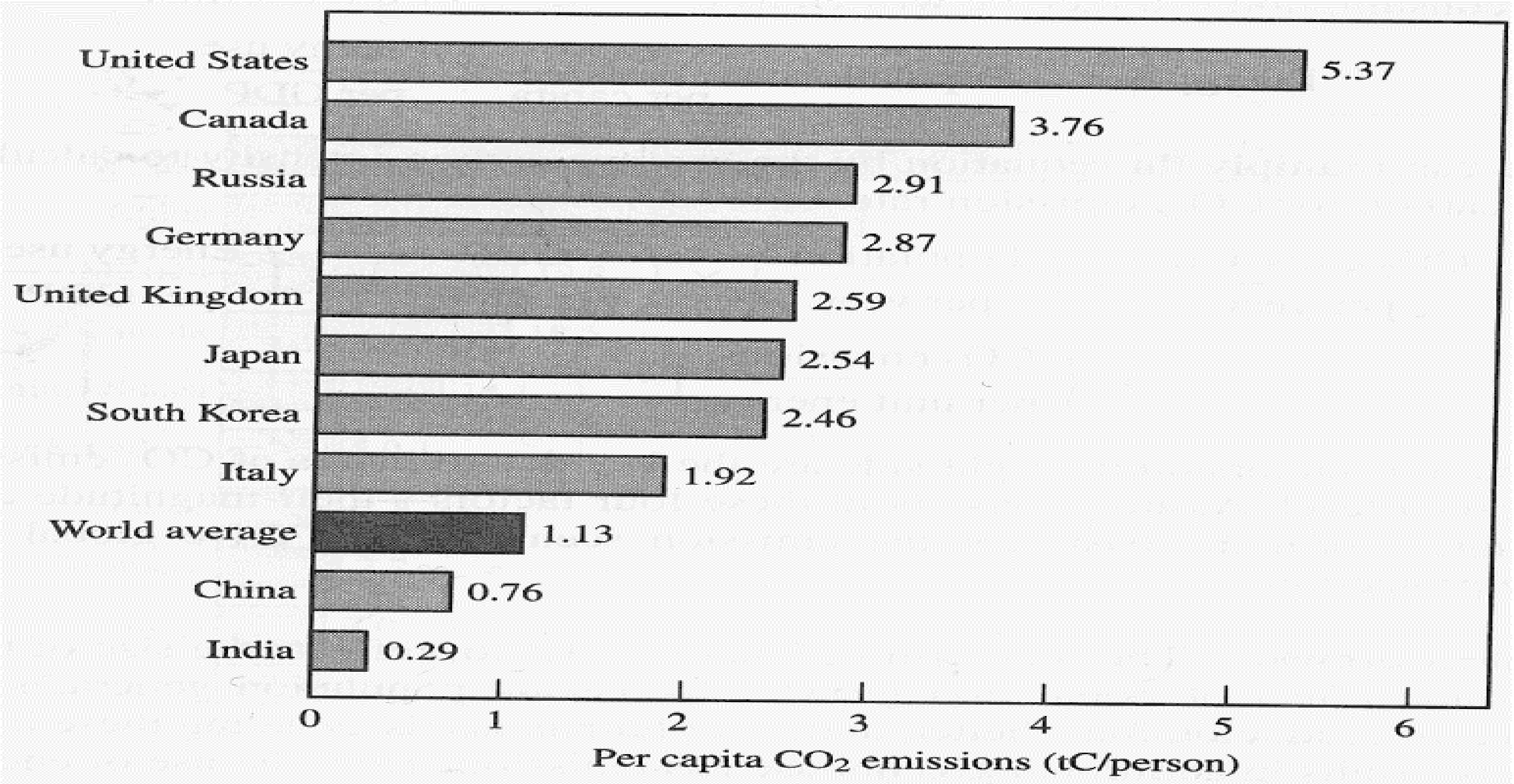
4. Achieving stabilization “slice by slice.”

Under each topic, give unsolicited advice to GCEP.

What if the fossil fuel future is robust, but the Greenhouse problem is severe?

		Will the fossil fuel system wither away?	
		YES	NO
Will the Greenhouse problem wither away?	YES	A nuclear or renewables world unmotivated by climate.	Assumed by most people in the fuel industries and most of the public
	NO	Assumed by most environmentalists	OUR WORKING ASSUMPTIONS

CO_2 emissions per capita from 10 largest emitting countries and world



Emissions in 1997. U.S. emissions are still growing. *From Marland et al., 1999.*

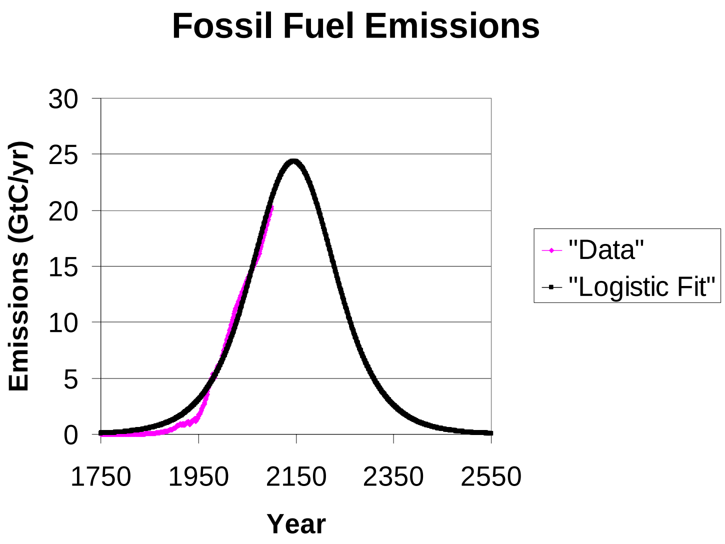
Rubin, p. 523

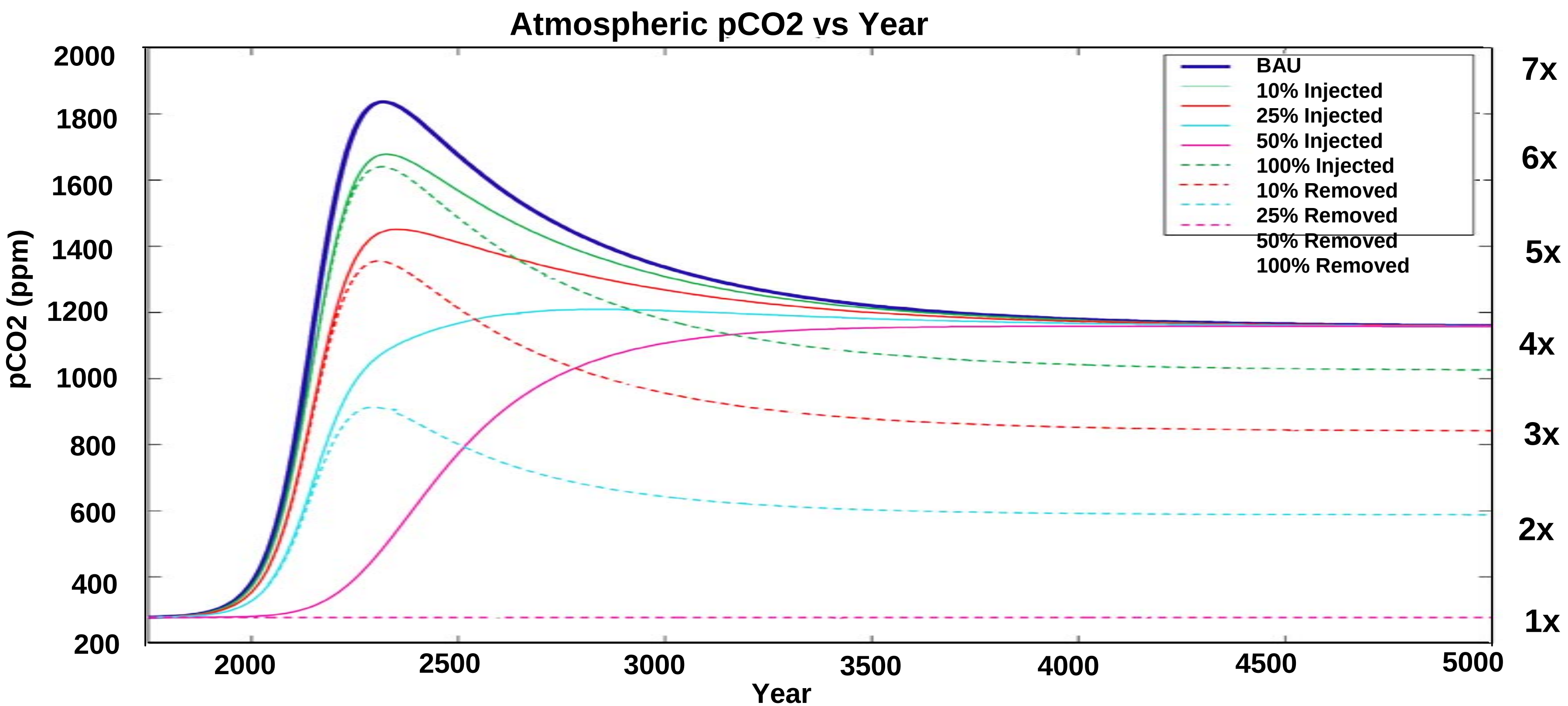
Global Fossil Carbon Resources, Gt(C)

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

Source Rogner, *Ann. Rev. Energy and Env. 22*, p. 249. Also used: 1 toe = 41.9 GJ; 20.3 kg(C)/GJ(oil); 13.5 kg(C)/GJ (gas); 24.1 kg(C)/GJ(coal).

What if 5600 Gt carbon were removed from below ground?





The Rosetta Stone

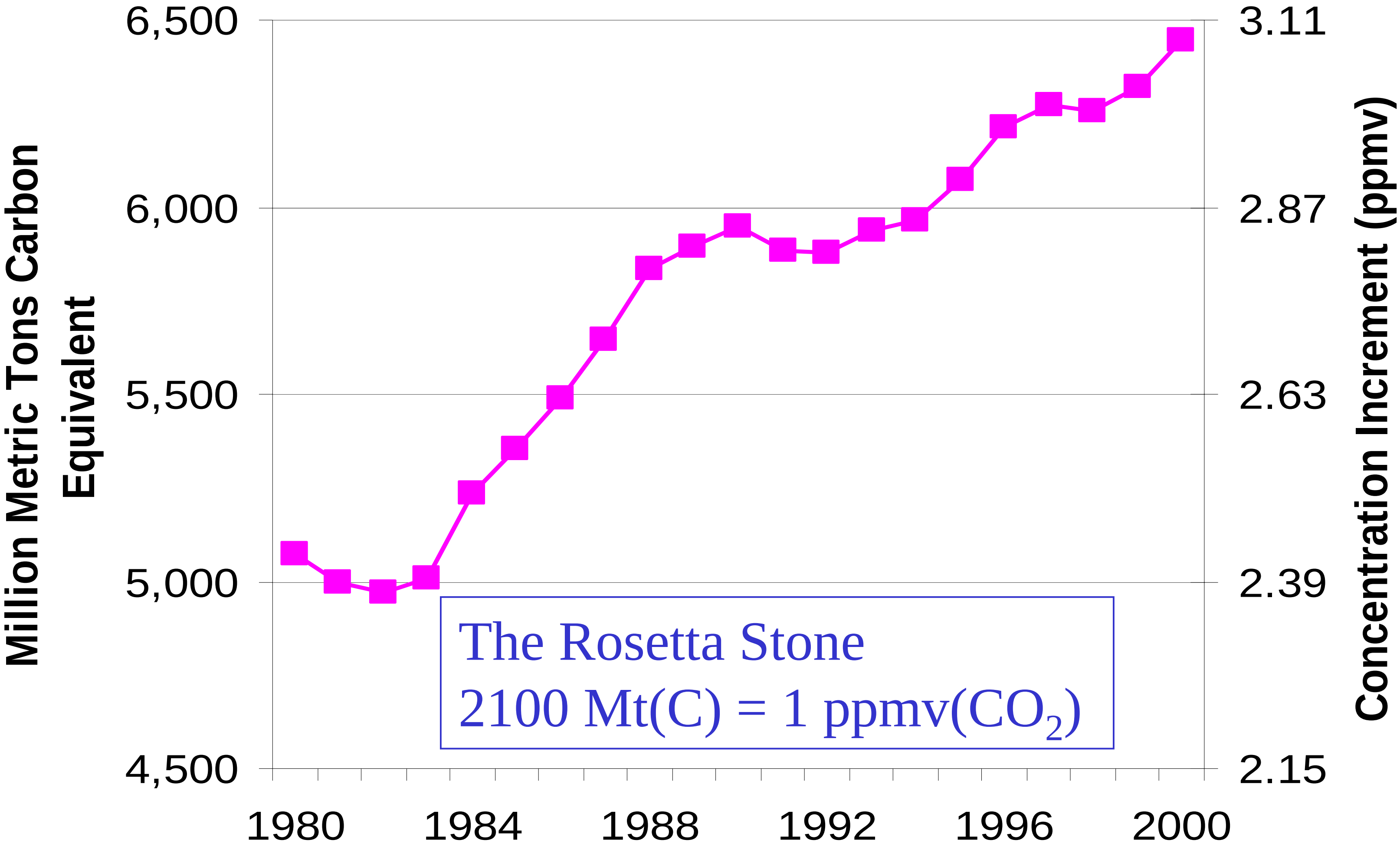
1 ppm(v) = 2.1 Gt(C)

This connects the worlds of energy and environmental science

Example: We are currently extracting from below ground and adding to the atmosphere about 6 billion metric tons of carbon per year. In our atmosphere, currently, about 370 of every million molecules are CO_2. A year from now, therefore, about 373 of every million molecules will be CO_2, if there are no removal mechanisms ("sinks").

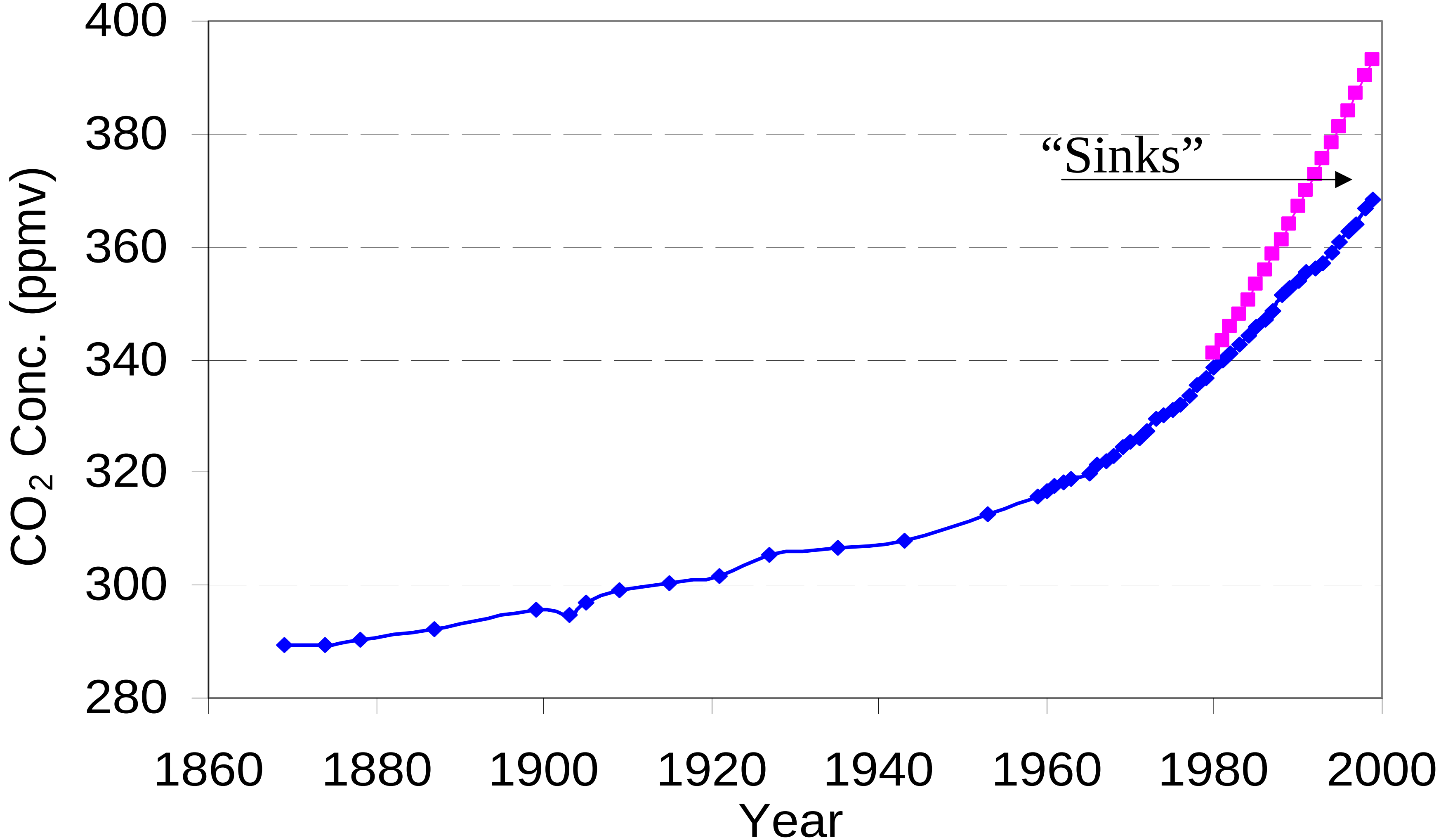
There *are* sinks, both land and ocean sinks. Today they remove CO_2 from the atmosphere at about half the rate that we are adding CO_2.

World Annual Carbon Dioxide Emissions: 1980-2000

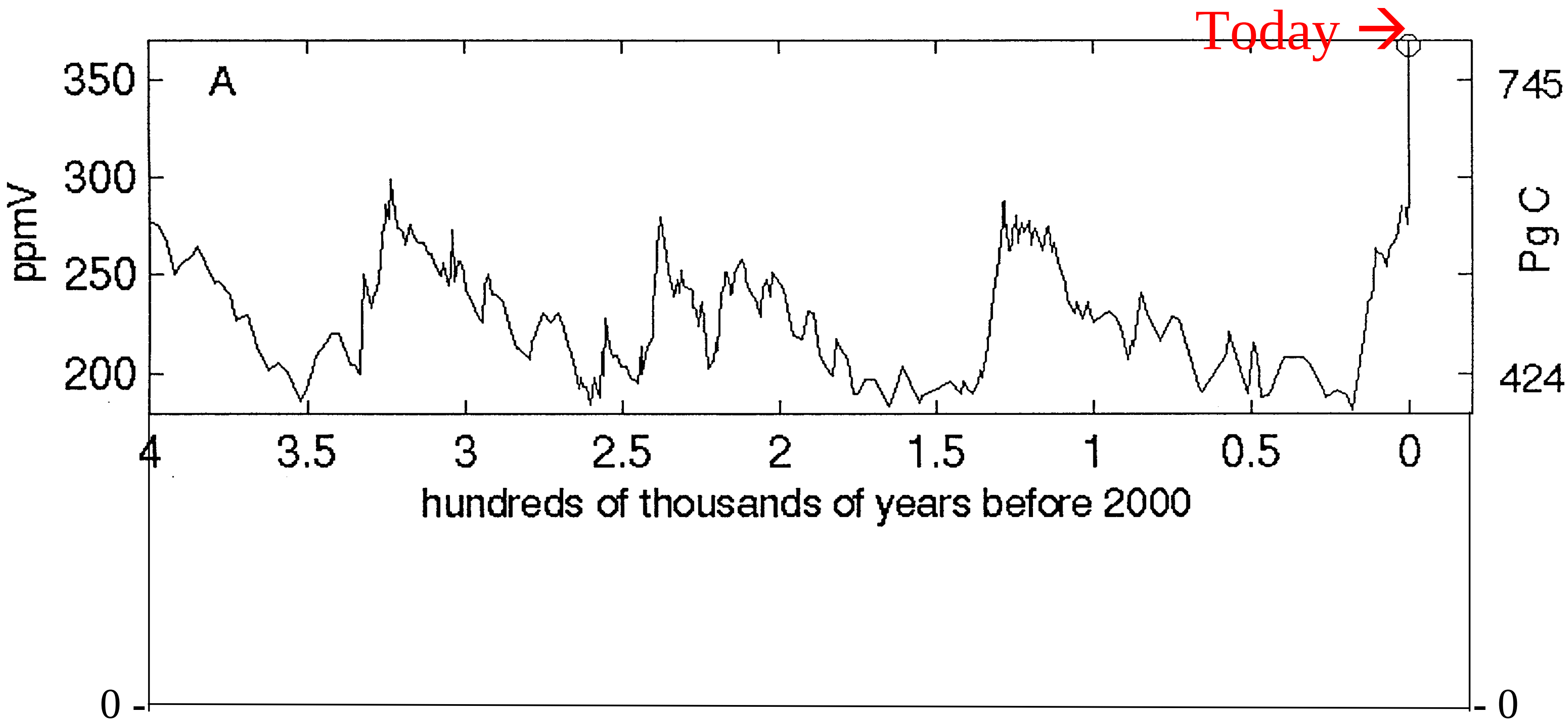


http://www.eia.doe.gov/emeu/international/total.html#IntlCarbon

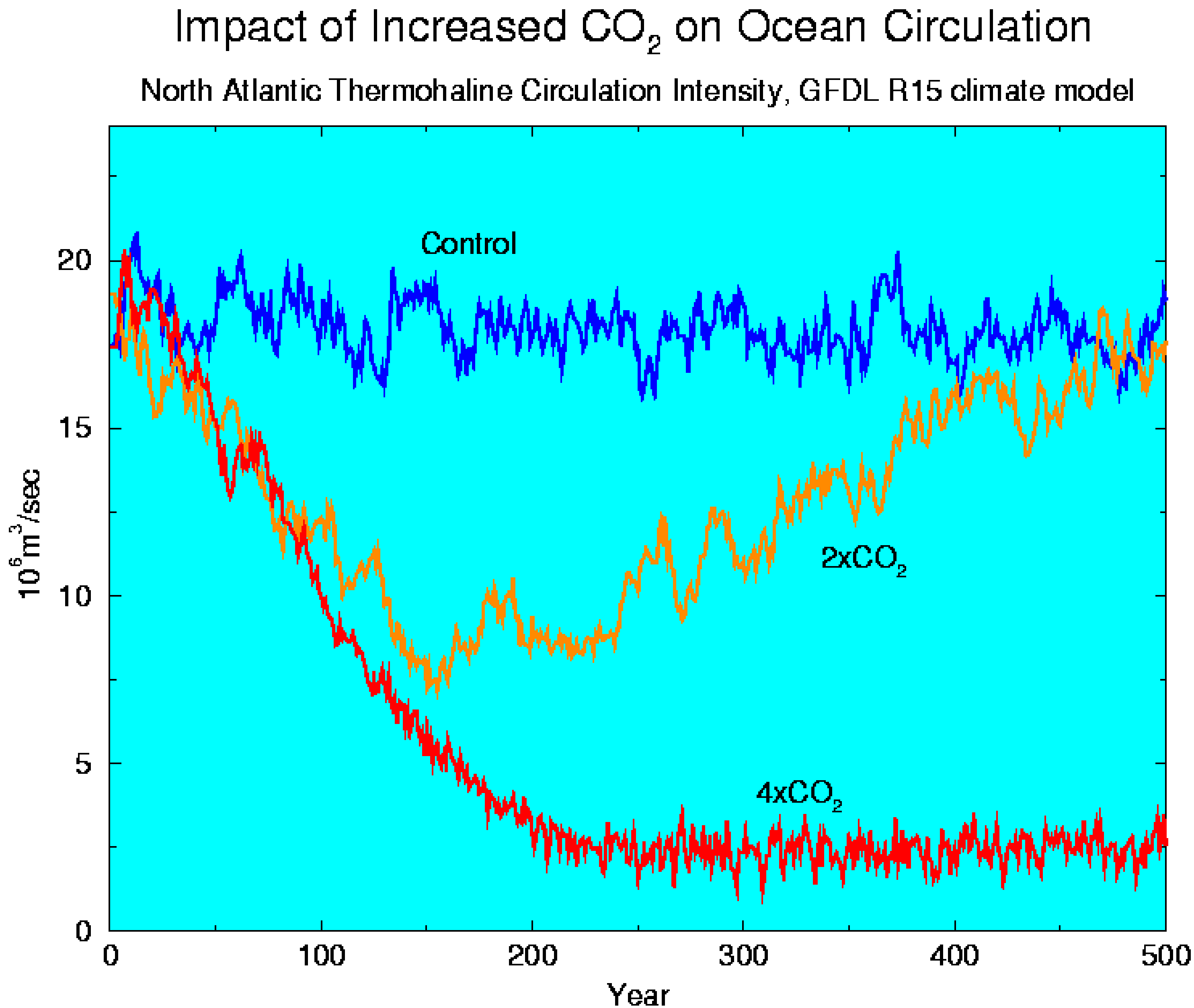
Atmospheric CO_2 Concentration with and without 1980-99 sinks



400,000 Years of CO_2 Data: Four Ice Ages



Variations of atmospheric CO_2 over glacial/interglacial times (Petit et al. 1999, Keeling and Whorf 1999). Circle at upper right shows current concentration.



Impact of Increased CO_2 on Ocean Circulation
North Atlantic Thermohaline Circulation Intensity, GFDL R15 climate model
Control
$2xCO_2$
$4xCO_2$
$10^6 m^3/sec$
0
5
10
15
20
0
100
200
300
400
500
Year

A loose consensus: Avoid doubling the pre-industrial concentration

Pre-industrial CO_2 concentration in atmosphere:	*280 ppm*
Today's value	*370 ppm*
Doubled value:	*560 ppm*

Doubling is the most widely used boundary between acceptable and unacceptable greenhouse-related environmental disruption. Doubling will occur after *roughly* the extraction of 1000 billion tonnes of fossil carbon. We are already one-third of the way there. We are heading for a doubling within *roughly* 50-75 years.

Is "doubling" the appropriate reference ratio? Here is where the important scientific uncertainties and human judgments are found.

Unsolicited advice #1

Incorporate environmental science into your research program.

Otherwise, you will not internalize answers to the key question: Why work so hard at this?

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The three-way competition among secondary fuels

In a carbon-constrained world, H_2 is in many three-way competitions: with *electricity* and with *carbon-carrying secondary fuels* (gasoline and diesel, aviation fuels, distributed natural gas).

The outcomes of these competitions will depend on further competitions at the point of use:

engines *vs* fuel cells *vs* batteries for motive power

furnaces *vs* heat pumps *vs* electric resistive heating *vs* solar heating for space heating.

Hydrogen *vs* carbon-carrying secondary fuels

***Relative to carbon-carrying secondary fuels*:**

H_2 use will not add carbon to the atmosphere – when produced from carbon-free primary energy (renewable or nuclear) or from fossil fuels with carbon capture and storage. [Exception: carbon fuels from biomass do not add carbon to the atmosphere either.]

H_2 may burn more cleanly in combustion engines.

H_2 is better matched to a fuel cell. It is credible that fuel cells will transform the energy system.

H_2 may compete poorly for home heating and personal transport, because of safety constraints on H_2 indoors.

Hydrogen *vs* electricity

Relative to electricity:

H_2 is a fuel.

Historically, fuels have competed well with electricity. Today only one third of primary energy produces electricity. Electric transport has found a role only in trains and vehicles of short range. Electric heating has found a role largely in mild climates.

An all-electric economy is a conceivable outcome of a carbon-constrained world, but it will require dramatic advances in energy storage and heat pumps.

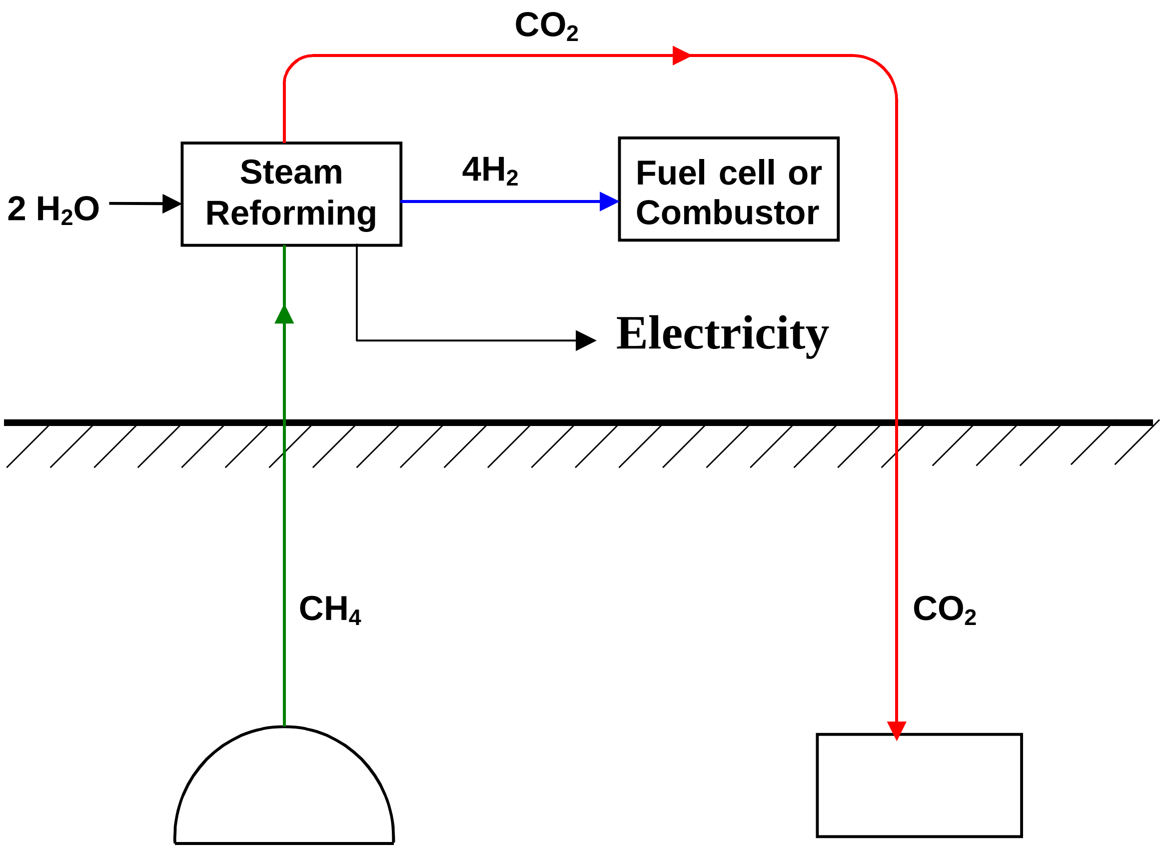
The carbon constraint is neutral between H_2 and electricity.

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.

Capture the Carbon in Fossil Fuels

Separate the energy content from the carbon content
Produce two C-free secondary energy carriers: electricity and H_2



The Carbon Refinery

The importance of hydrogen for distributed uses leads to an energy system that:

–produces hydrogen centrally from fossil fuels, while capturing carbon

–distributes hydrogen to end users and carbon dioxide to storage sites through two new infrastructures

–uses hydrogen productively at end use

The coal power plant, the petroleum refinery, and the natural gas “refinery” converge at the *Carbon Refinery*.

The carbon refinery produces a variety of fuels and chemicals, exports electricity, and captures CO_2 . Over time, a larger fraction of the product is H_2.

The Wabash River
Coal Gasification Repowering Project

Captured Carbon: Stored How?

Storage forms:

1. CO_2 as a dense ("supercritical") fluid
2. CO_2 in aqueous solution
3. solid graphite
4. carbonate minerals
5. biological materials

Storage locations:

1. deep below ground (including deep below the ocean floor)
2. in hydrocarbon (oil, gas, coal) formations
3. deep in the ocean
4. very deep on the sea floor
5. above ground
6. below ground in soil

Color: Current projects


STATOIL

CO_2 Infrastructure Studies
Natural CO_2 fields in southwest U.S.

- McElmo Dome: 0.4Gt(C) in place
- Pipeline from McElmo to Permian Basin: 800 km

Two conclusions:

1. CO_2 in the right place is valuable.
2. CO_2 from McElmo was a better bet than CO_2 from any nearby site of fossil fuel burning.

Near McElmo Dome, Colorado (from David Hawkins, NRDC)

“A sign about every quarter-mile” in the Canyons of the Ancients National Monument, Southwest Colorado.

Start Now to Gain Experience with the Permitting of Storage Sites

•*Public approval* – Openness, fairness, vigilance, responsiveness

•*Goals* – What constitutes victory? Retention time of 500 years?

•*Storage integrity* – Escape of CO_2 from a few sites is inconsequential. How can permitting include permission to fail?

•*Site-specific issues* –Local risks to health (drinking water), property (earthquakes), environment (vegetation). Ownership and liability.

•*Co-sequestration* – Can co-capture and co-storage allow avoidance of pollution controls (S, N, Cl, Hg)?

•*Learning* – Embed science in first projects. Instrumentation for model verification, hazard assessment, leak detection, generalization.

Uncertainties of permitting could dominate total sequestration costs.

Unsolicited advice #2

In developing your research agenda, give a prominent role to hydrogen production from fossil fuels with CO_2 capture.

Hydrogen from fossil fuels is strikingly underemphasized in this workshop.

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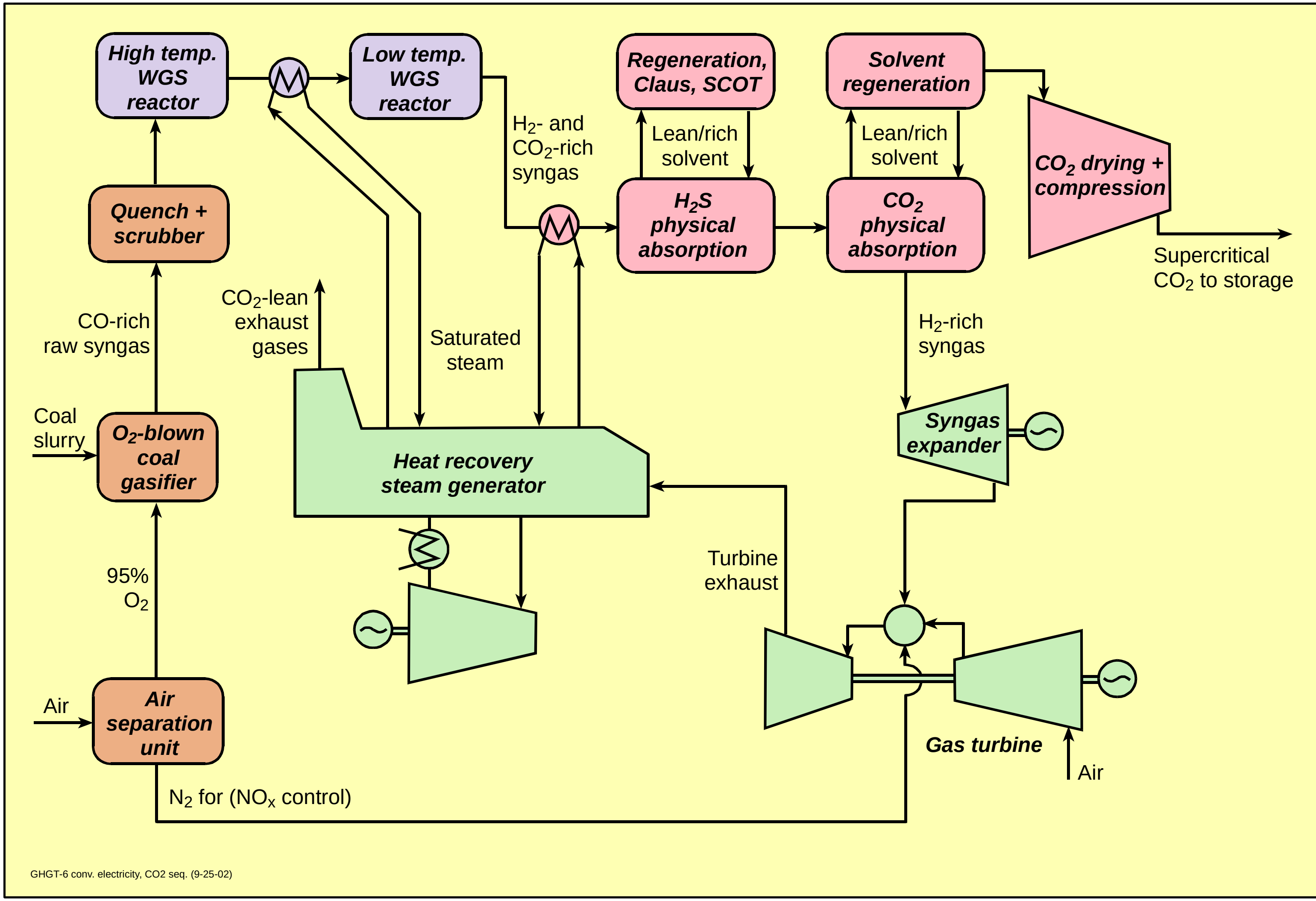
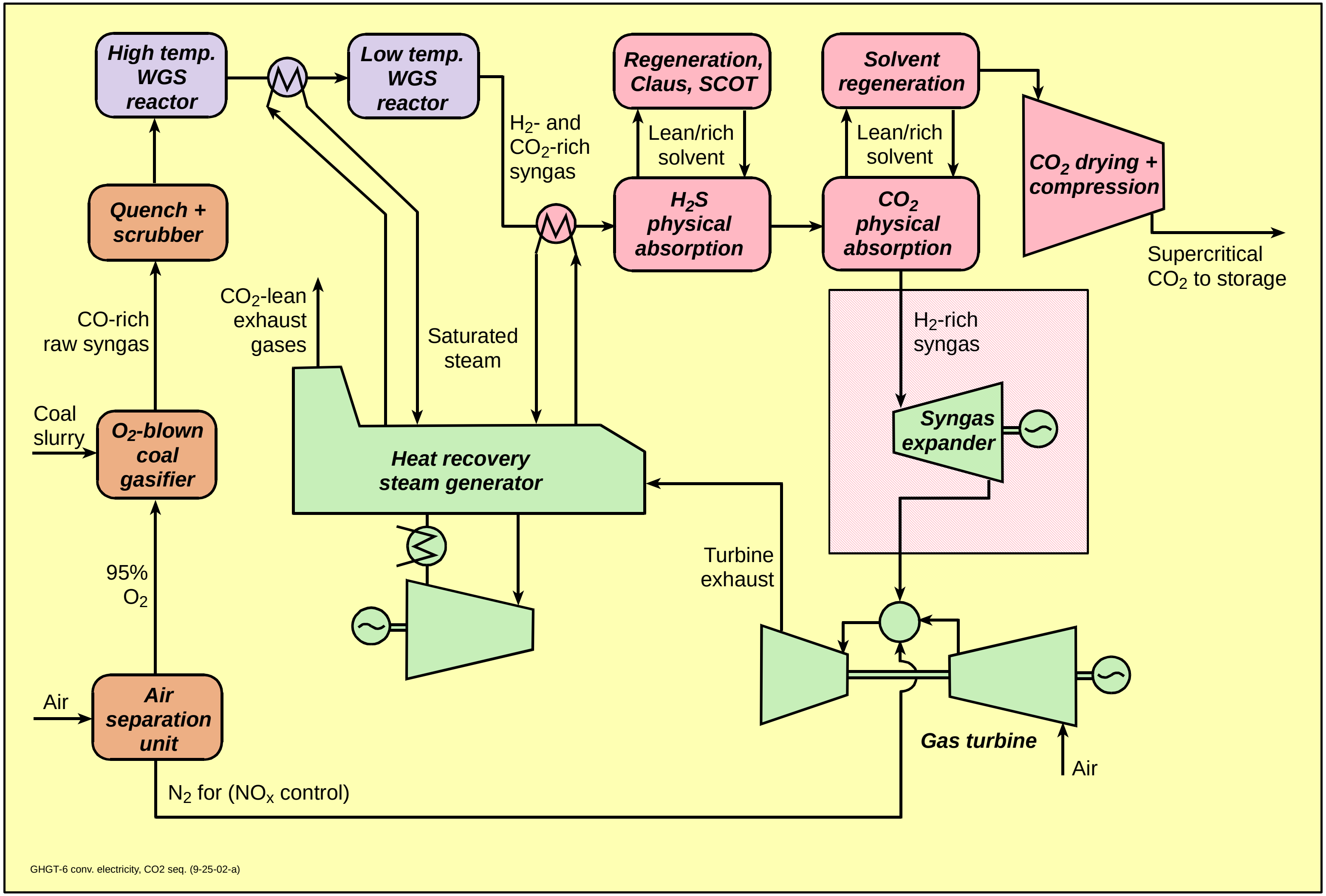
Benchmark: IGCC Electricity with CO_2 Capture



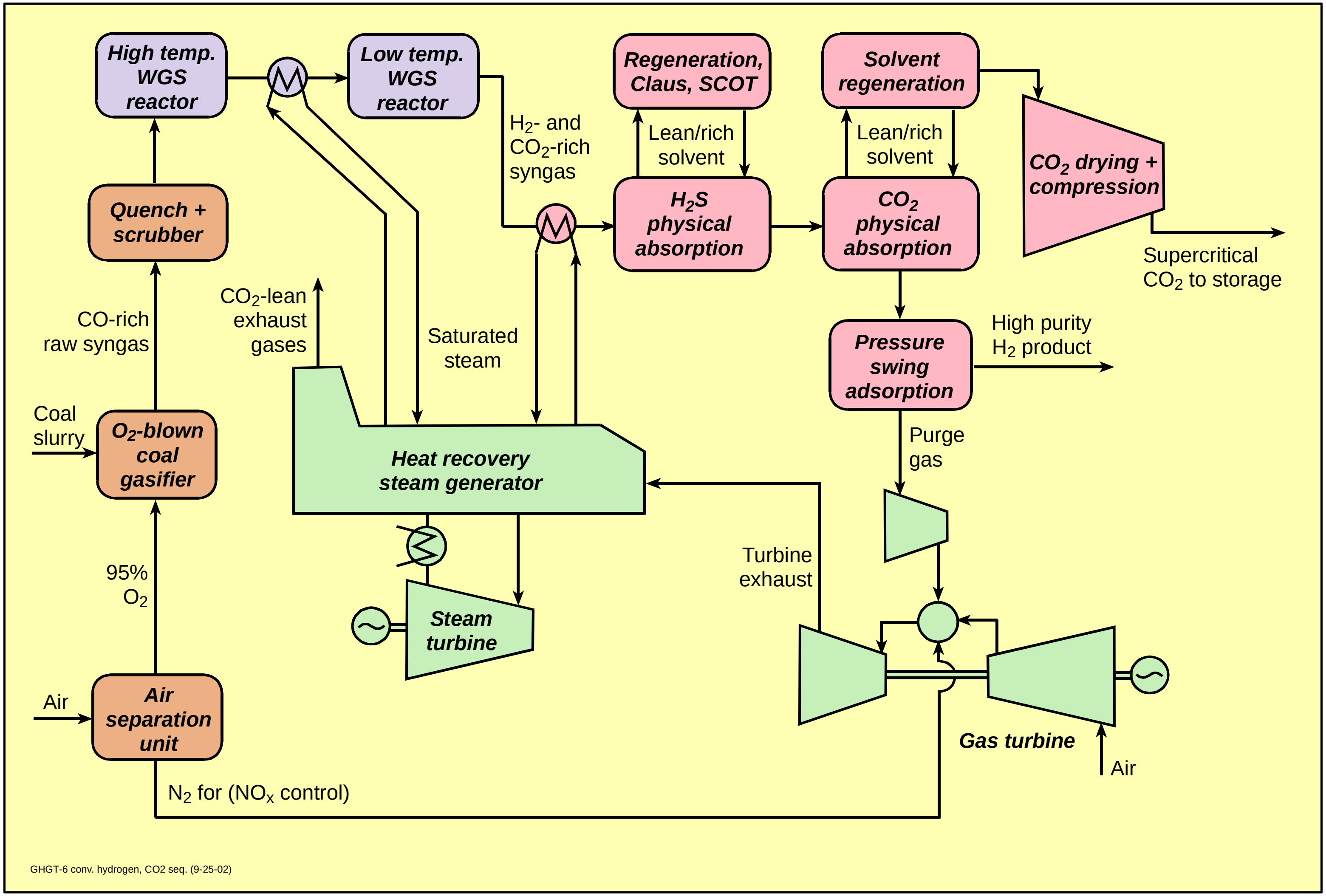
- Cost: 6.4 ¢/kWh. Efficiency: 34.8% (HHV). Assumes 70 bar gasifier with quench cooling. Plant scale is 368 MW_e.

H_2 Production: Add H_2 Purification/Separation



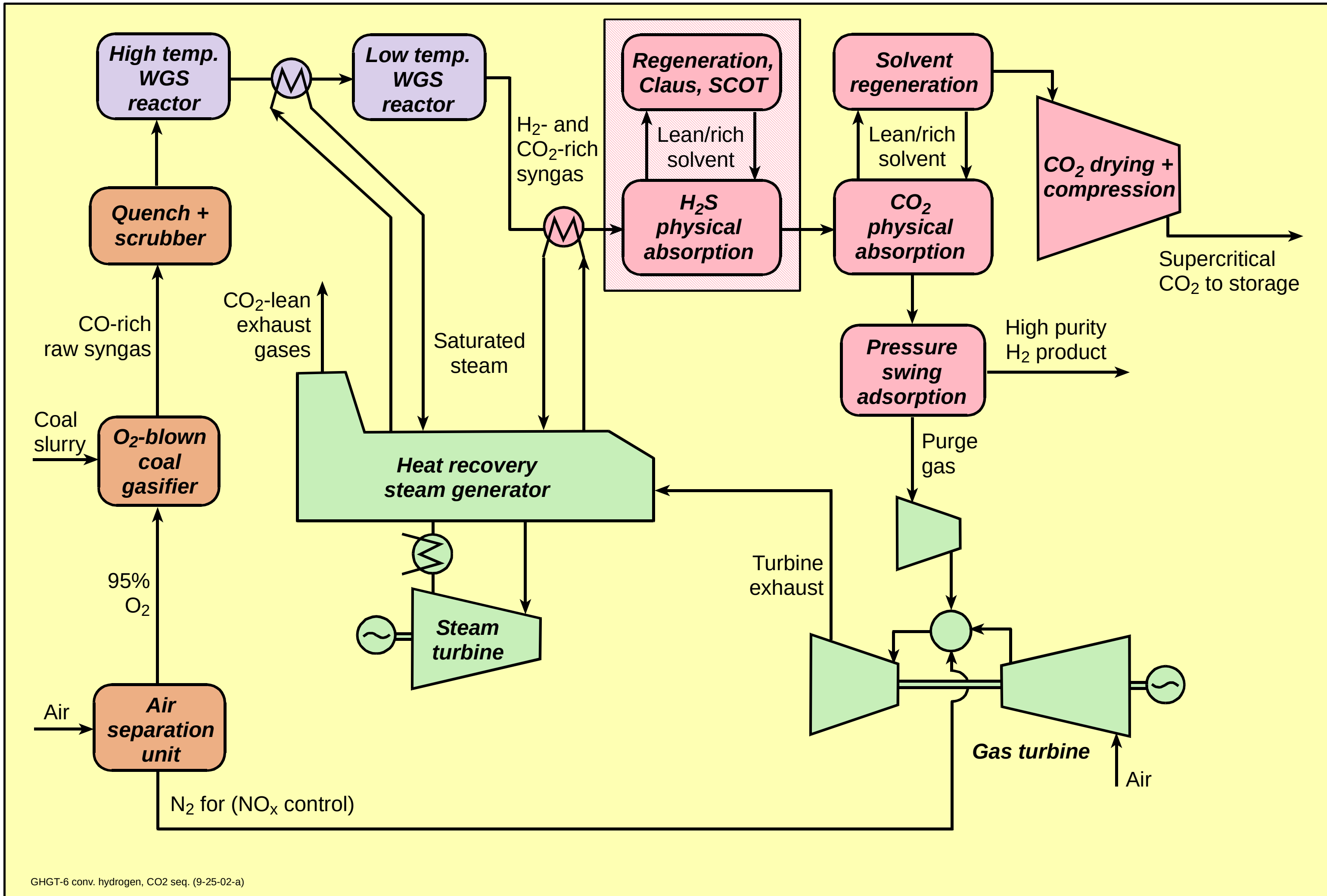
- Replace syngas expander with PSA and purge gas compressor.

Conventional H_2 Production with CO_2 Capture



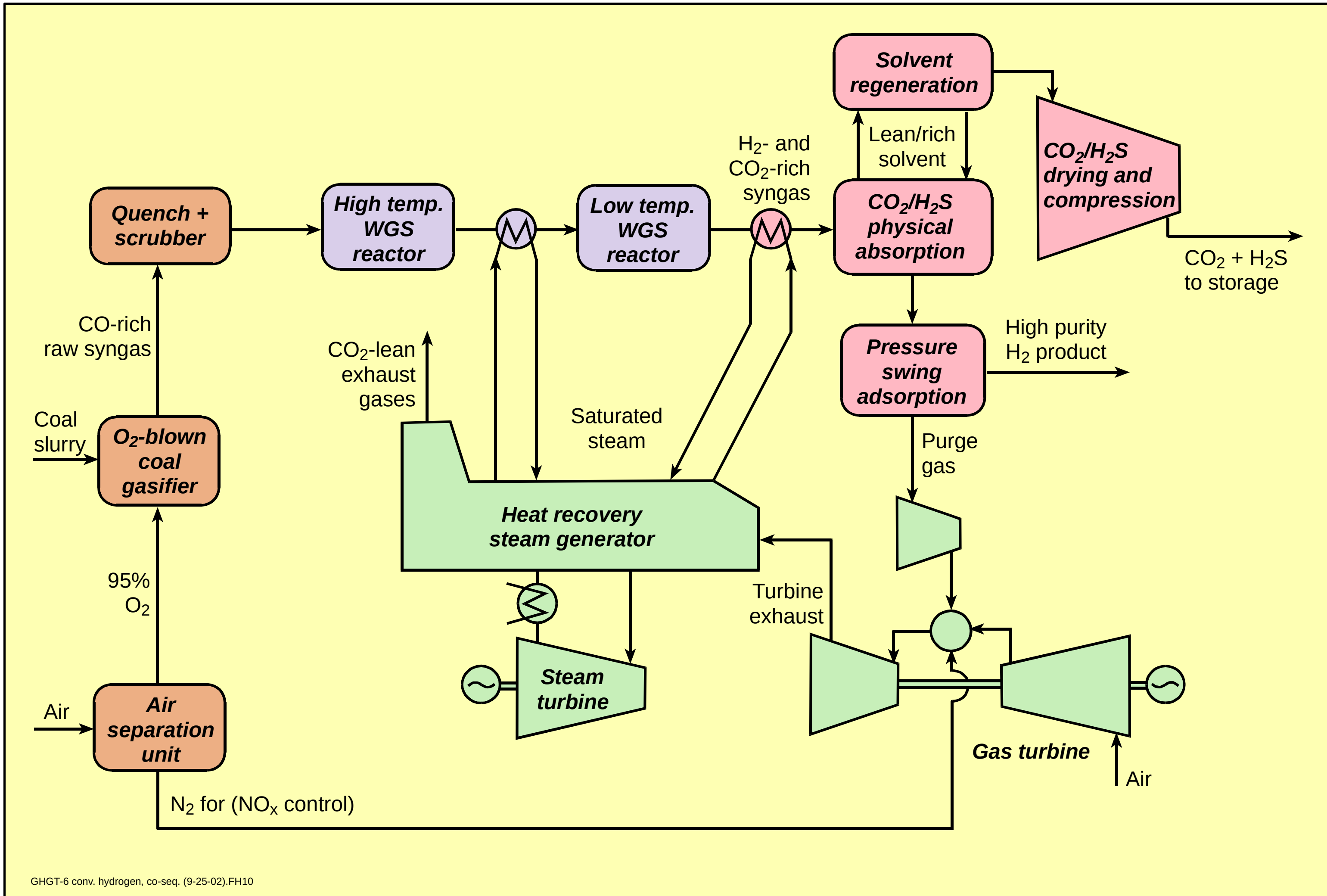
- H_2 cost: 7.5 \$/GJ (HHV). Assumes 70 bar gasifier with quench cooling. Plant scale is 1210 $MW_{th}(H_2)$ (HHV). Byproduct electricity is 4.6 ¢/kWh.

Capture (and Co-sequester) H_2S with CO_2



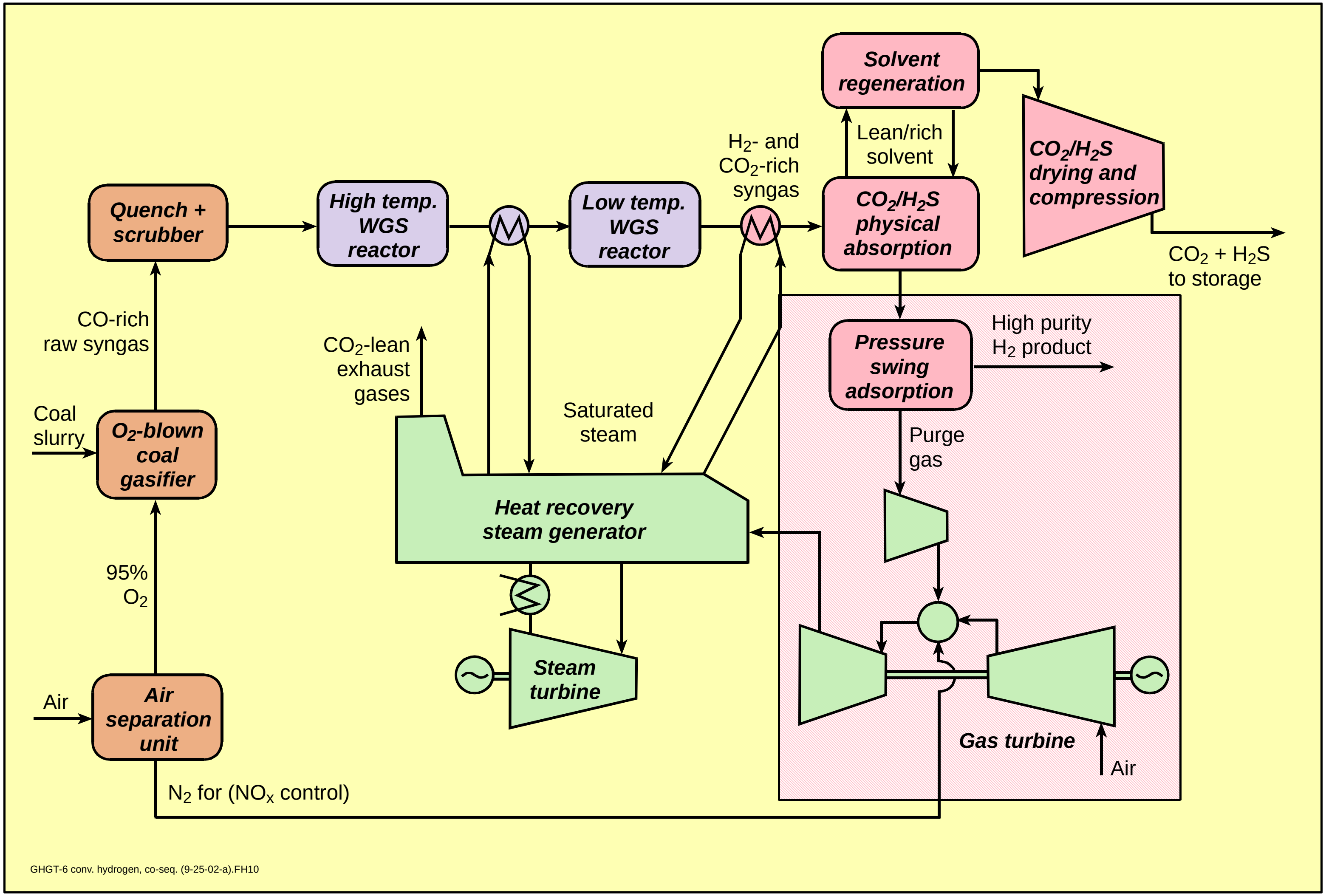
- Remove the traditional acid gas recovery (AGR) unit.

Conventional H_2 Production with CO_2/H_2S Capture



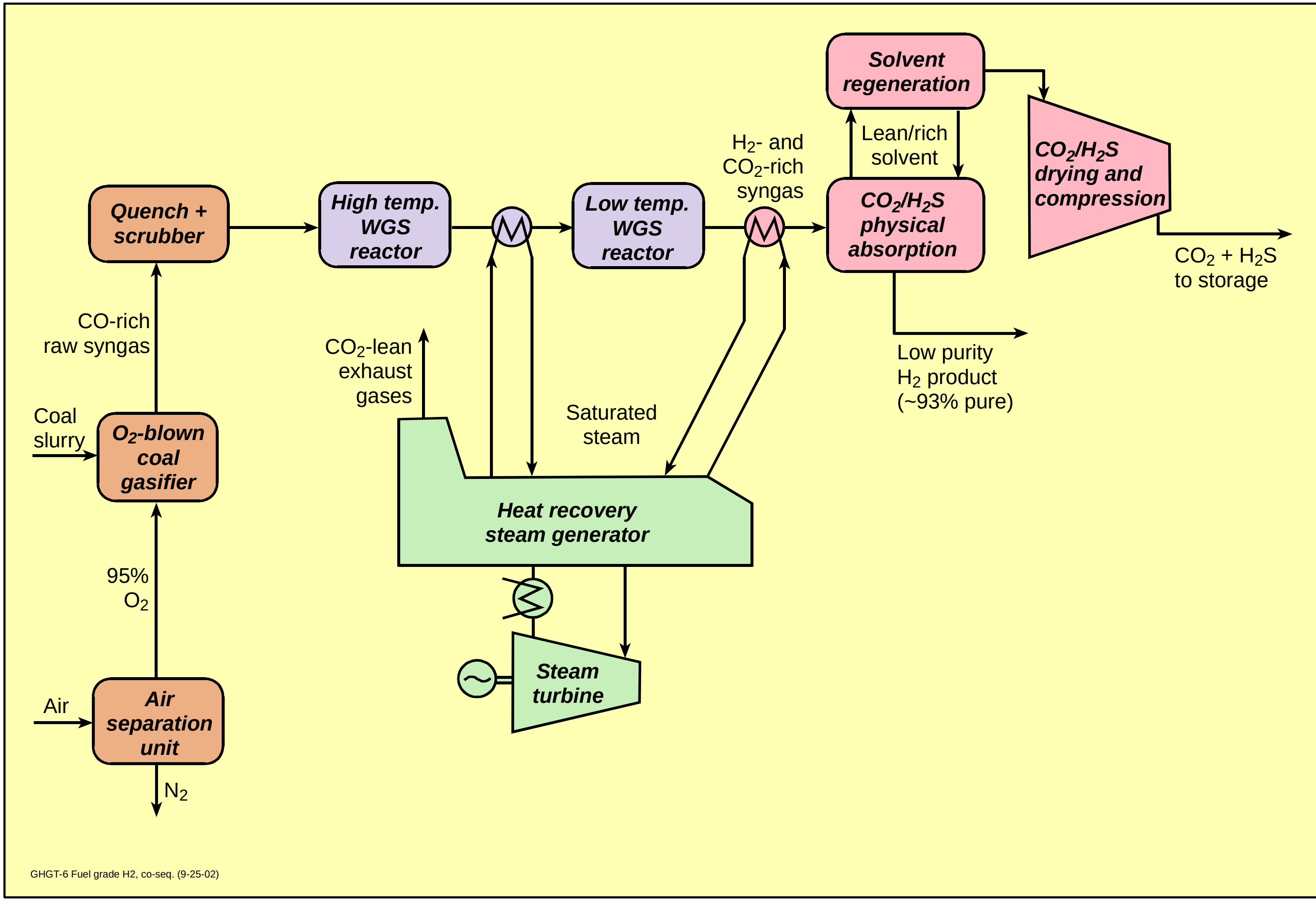
- Resulting system is simpler and cheaper.

Produce "Fuel Grade" H_2 with CO_2/H_2S Capture



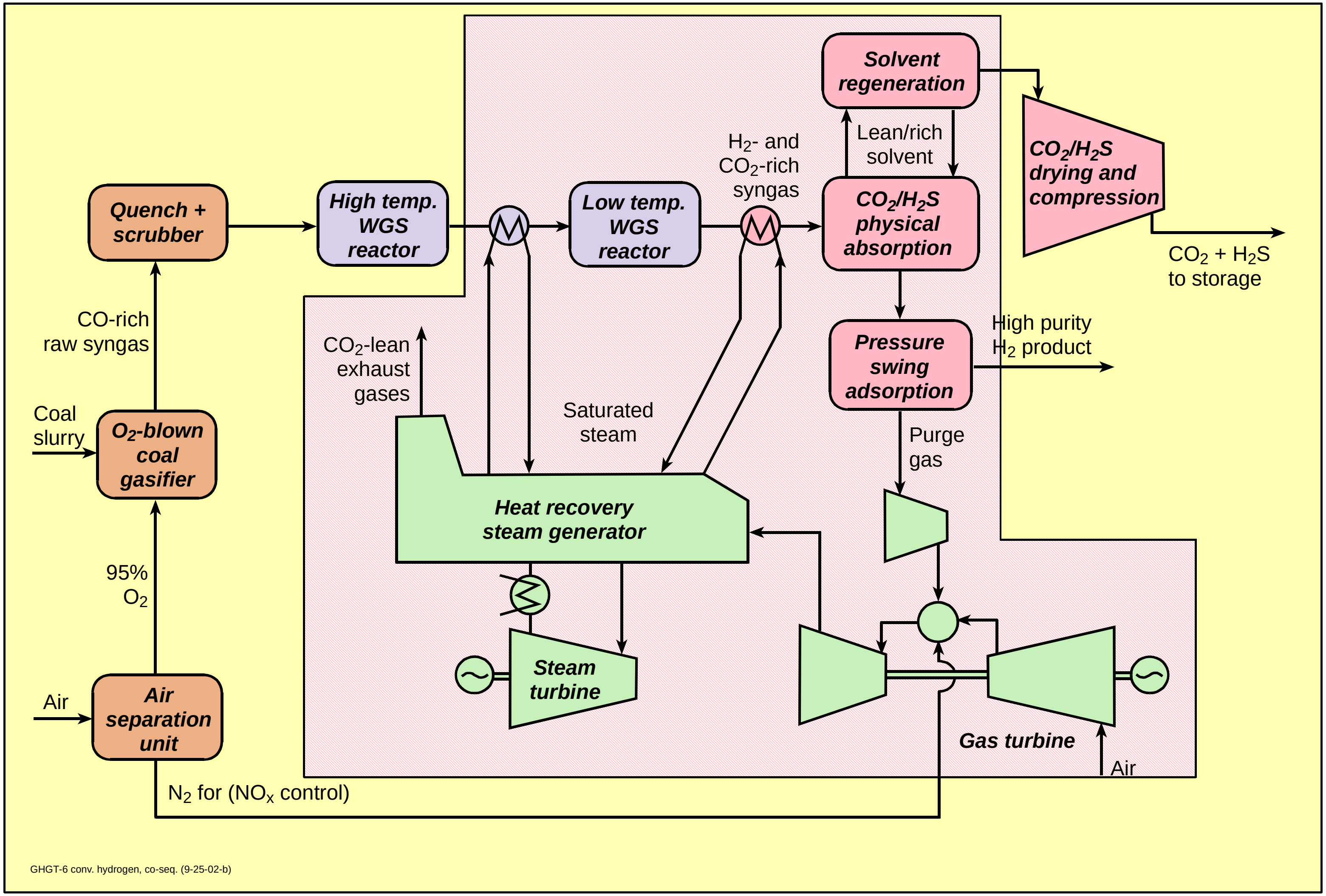
• Remove the PSA and gas turbine; smaller steam cycle.

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



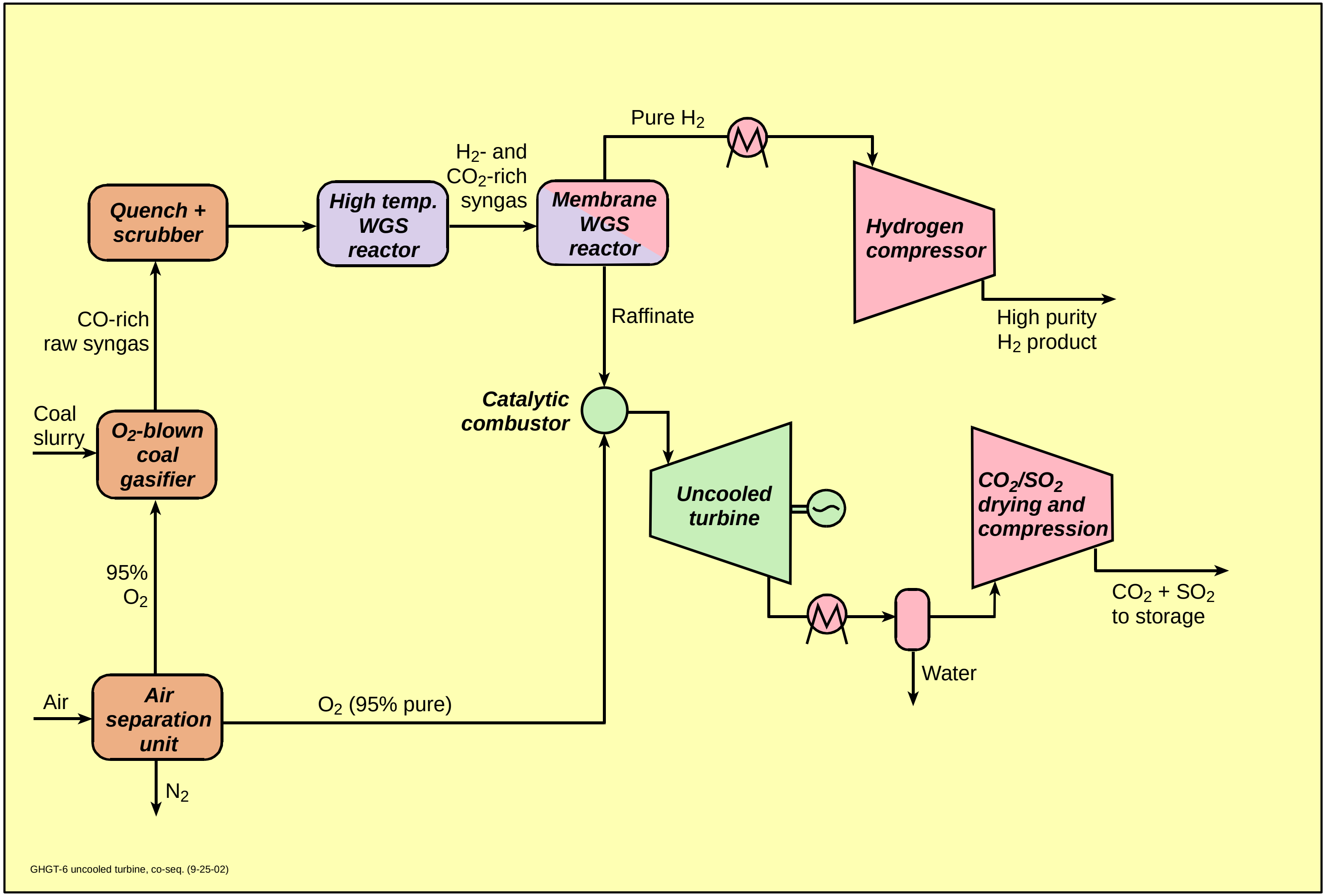
- Simpler, less expensive plant. No novel technology needed.

Change H_2-CO_2 Gas Separation Scheme



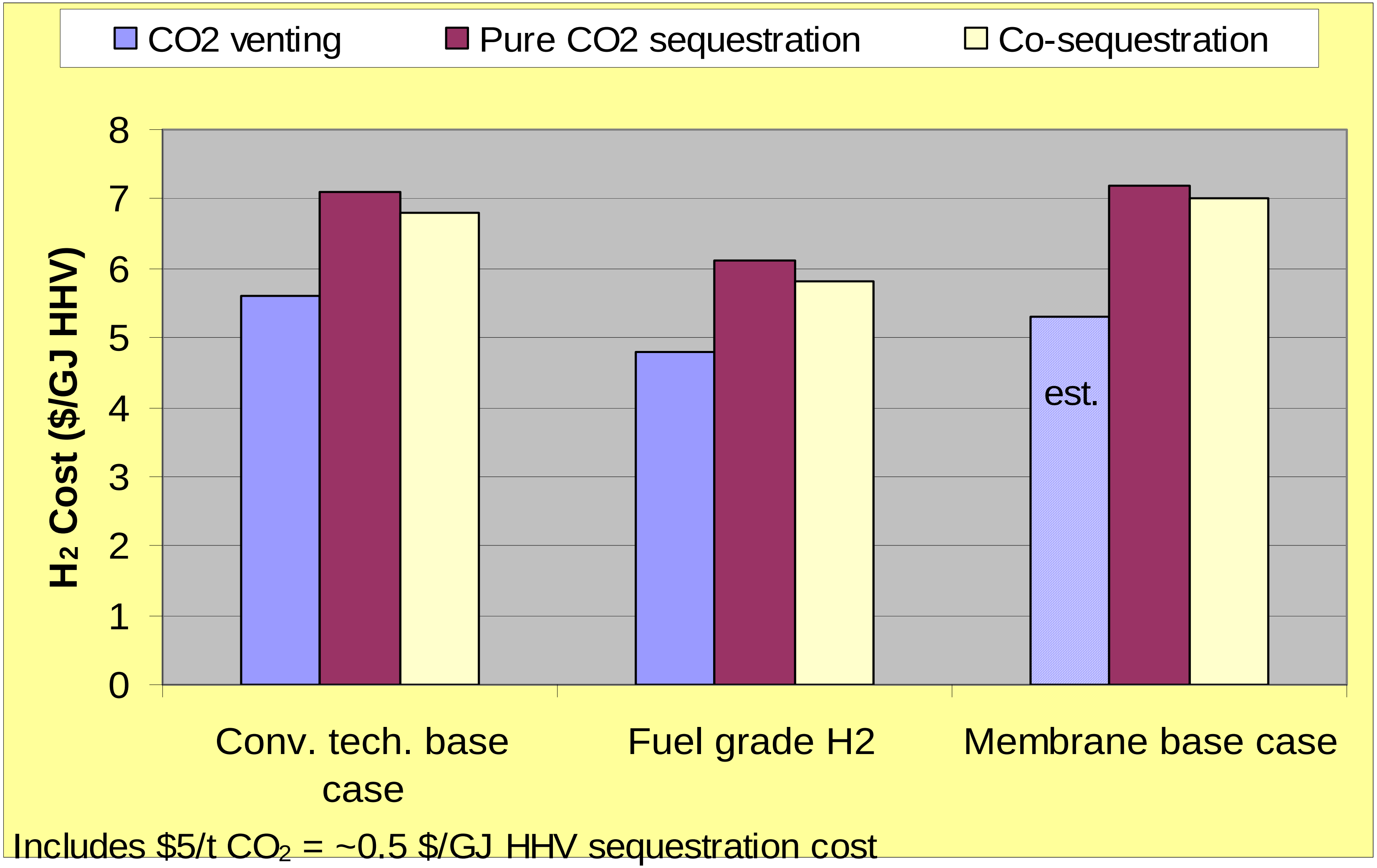
- Use membrane to separate H_2 from the syngas instead of CO_2.

H_2 Separation Membrane Reactor System



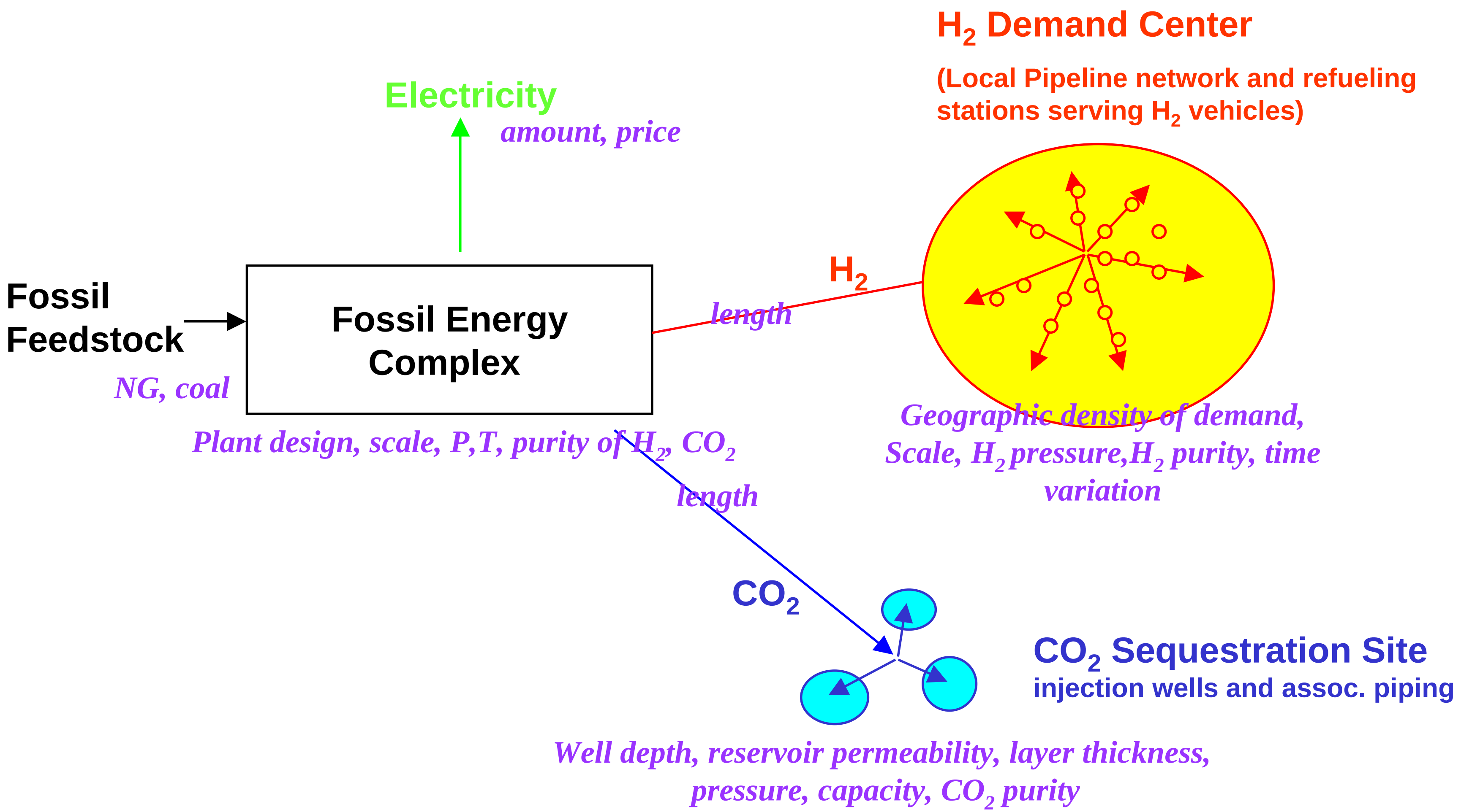
- Employ a H_2 permeable, thin film (10 μm), 60/40% Pd/Cu (sulfur tolerant) dense metallic membrane, configured as a WGS membrane reactor.

Cost of H_2 Production

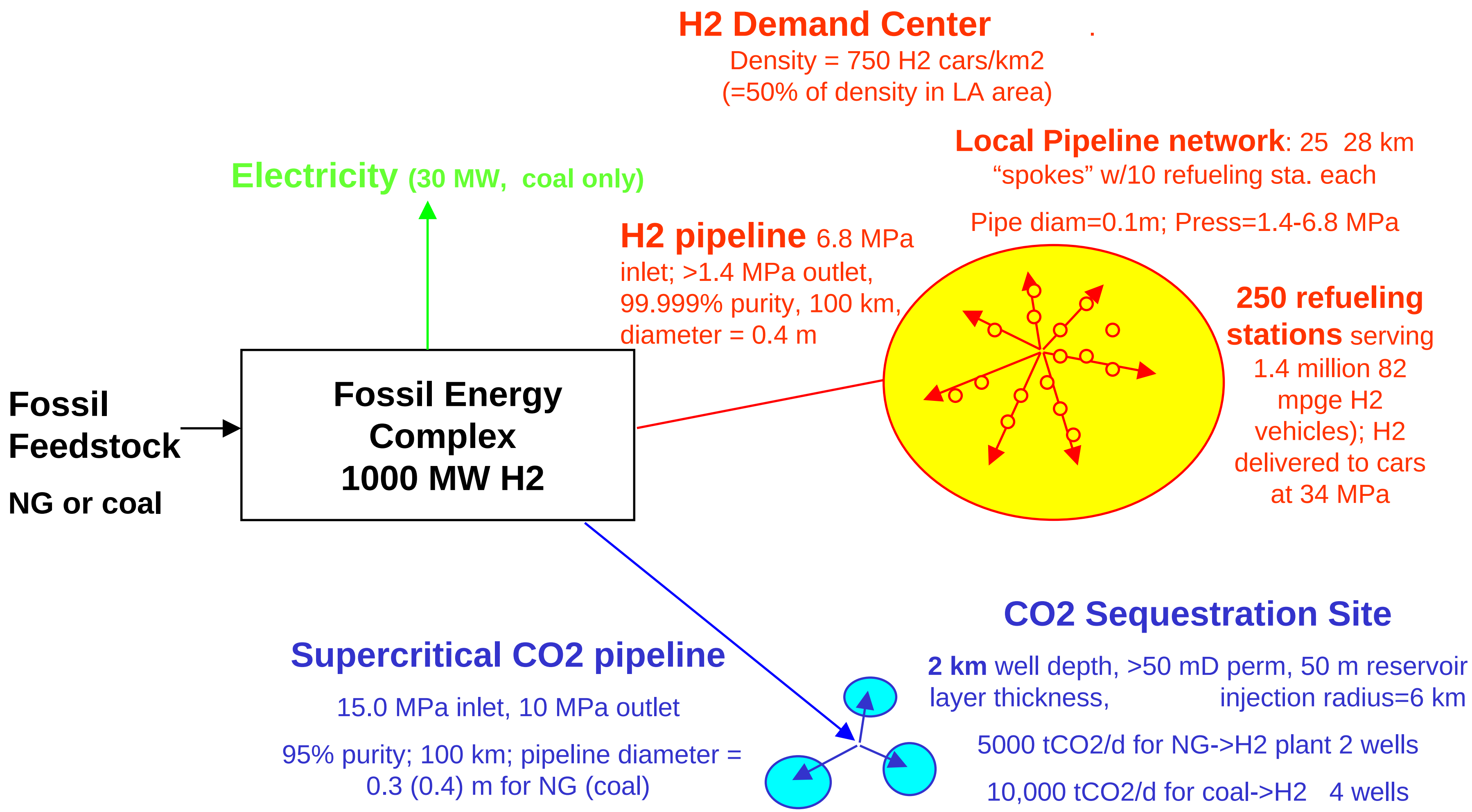


Membrane base case is for a Pd/Cu membrane.

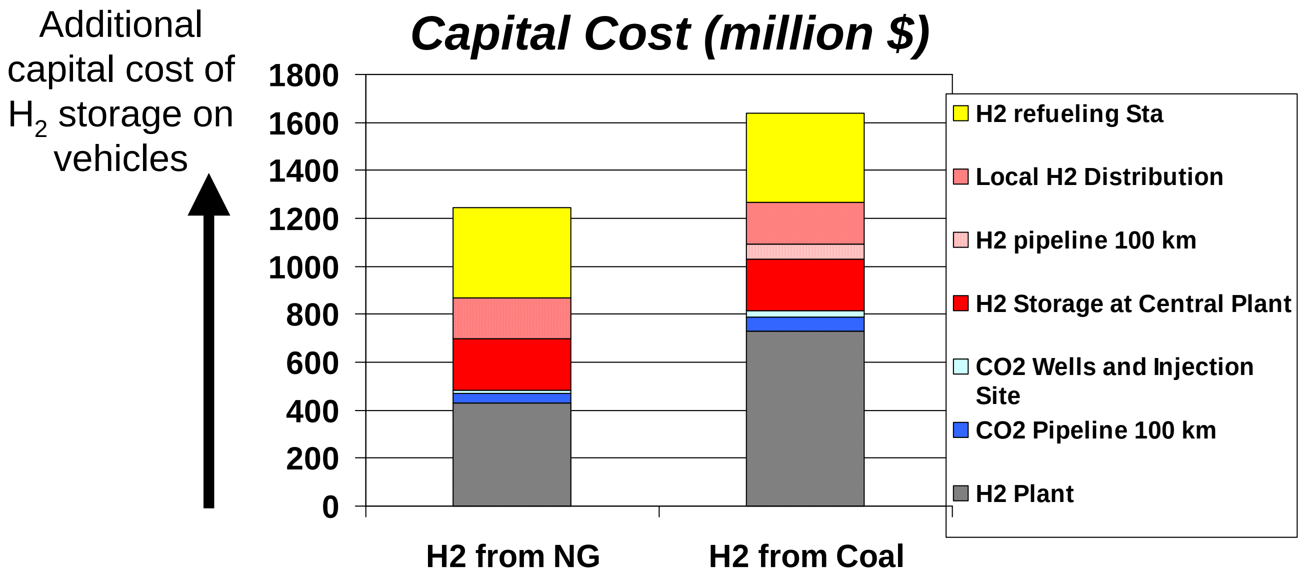
Hydrogen System *(Joan Ogden)*

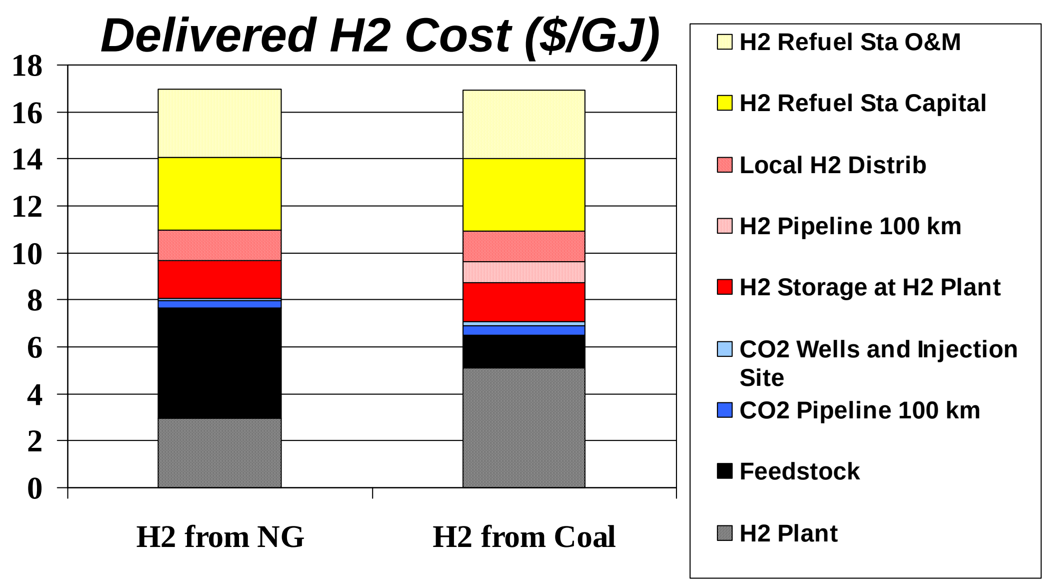


Base Case System



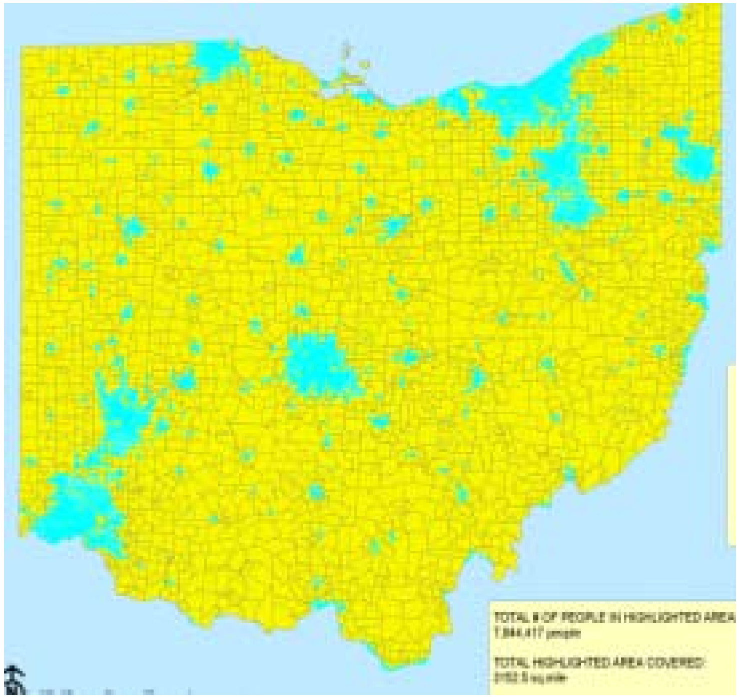
Economics of Base Case System





LOCAL H_2 PIPELINE DISTRIBUTION

Assume All Light Duty Vehicles Use H_2, and Threshold for Building a H_2 Local Pipeline is 200 Cars/km^2



Columbus, Cleveland, Cincinnati could each support a large coal H_2 plant dedicated to fuel production.

Many smaller cities have demand <u>dense</u> enough for local H_2 distribution, but not <u>large</u> enough for their own coal H_2 plant. Make H_2 at smaller scale (from NG or elec) or pipe or truck H_2 to these cities.

Unsolicited advice #3

Investigate materials, catalysts, and sensors that can improve hydrogen production from fossil fuels.

Investigate retail delivery of hydrogen.

Seek technological insights into hydrogen safety.

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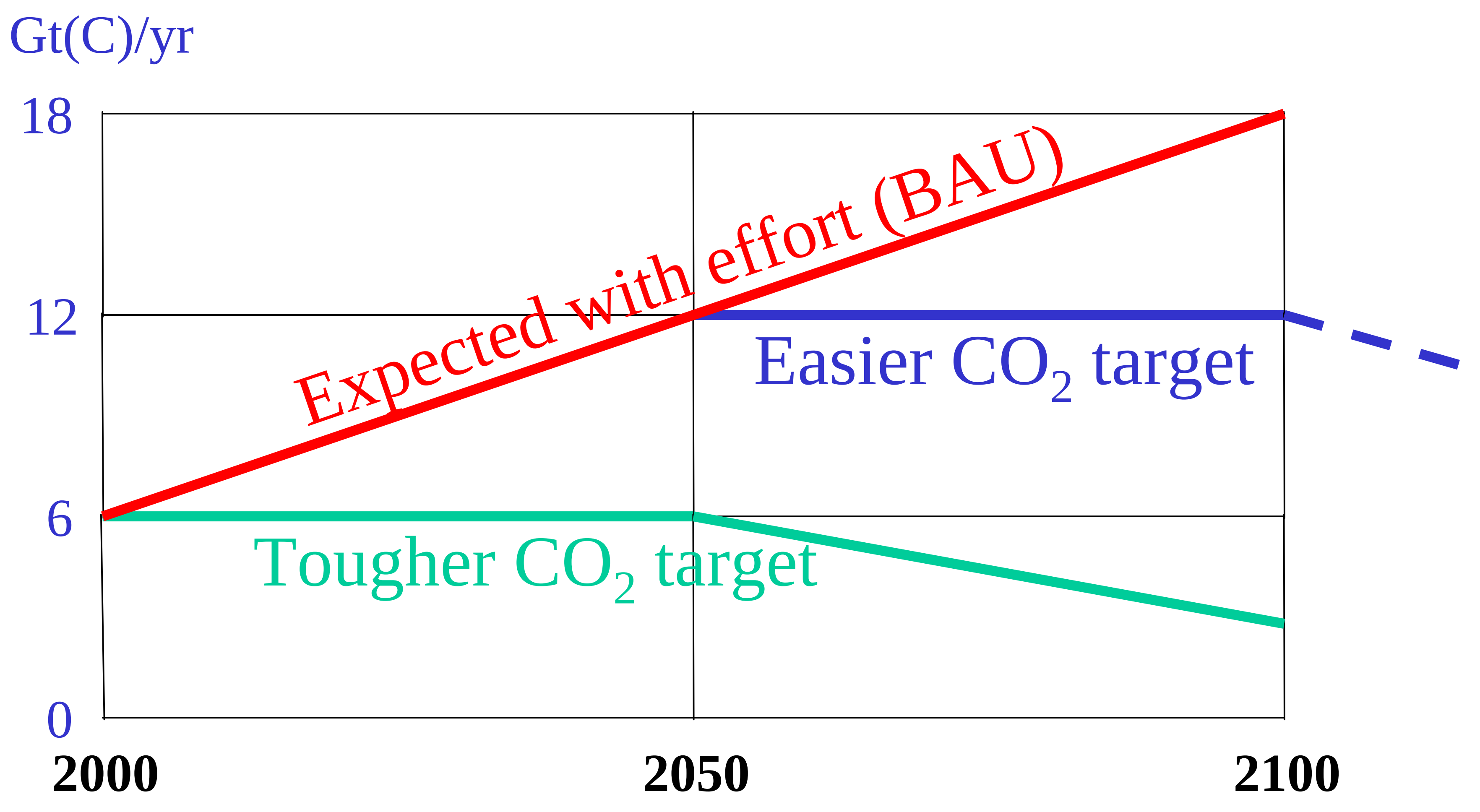
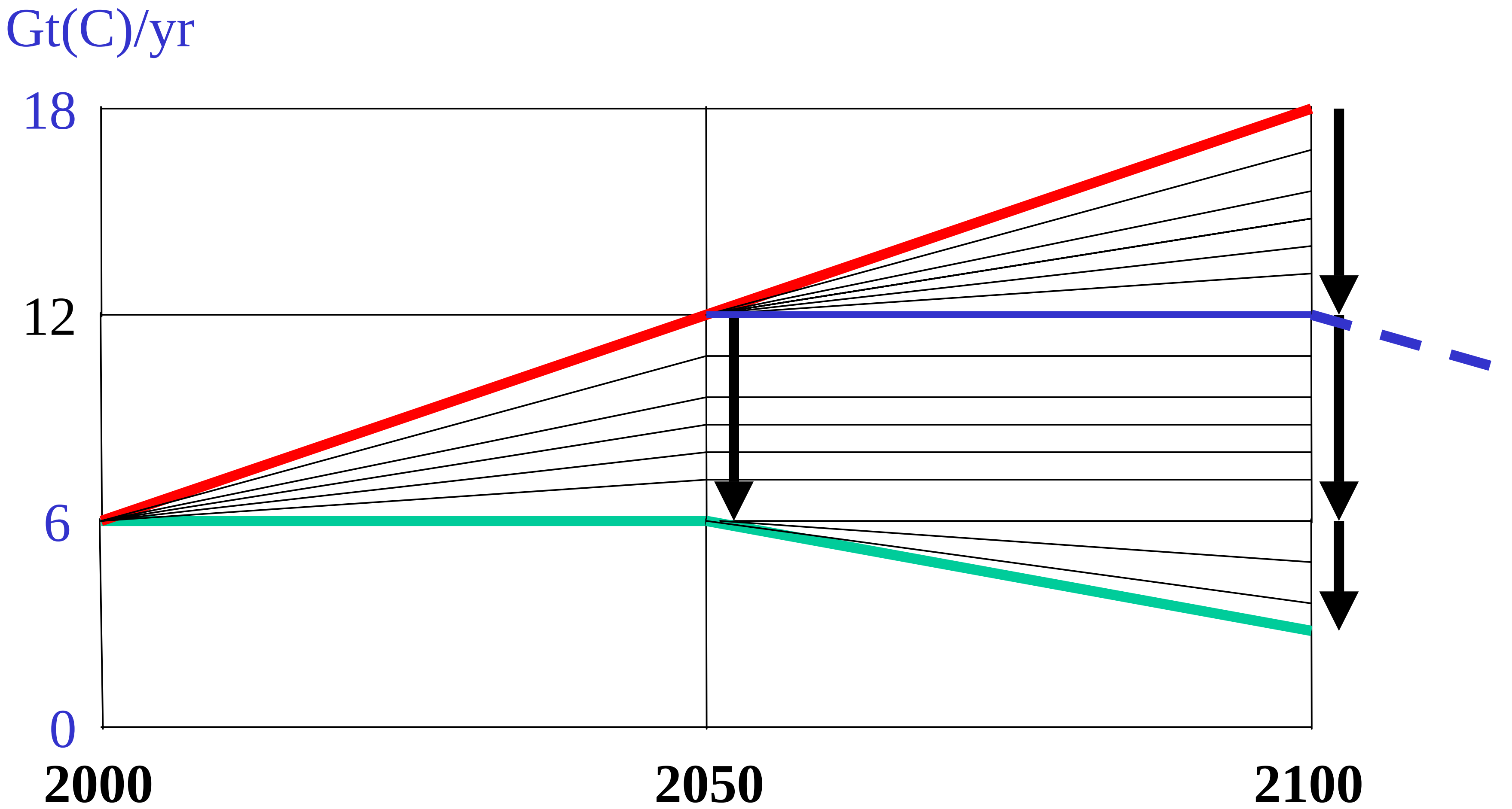
Urgency depends on the stabilization target



15 “slices”

A “slice” is an activity that reduces the rate of carbon build-up in the atmosphere and that grows in 50 years from zero to 1.0 Gt(C)/yr.



Achieving stabilization, slice by slice (p.1 of 2)

Mitigation	**1 Gt(C)/yr Global Business**	**Risk, Impact**
Coal plant: CO_2 stored, not vented	700 1GW plants	CO_2 leakage
Nuclear displaces average plant	1500 1 GW plants (5 x current)	Nuclear proliferation and terrorism, nuclear waste
Wind displaces average plant	150 x current	Regional climate change?, NIMBY
Solar PV displaces average plant	2000 x current; $5x10^6$ ha	Minimal
Hydrogen fuel	1 billion H_2 cars (CO_2-emission-free H_2) displace 1 billion 30 mpg gasoline/diesel	H_2 infrastructure; H_2 storage
Efficiency, overall	8% of 2050 “expected” fossil C extraction	Minimal
Efficiency, vehicles only	2 billion gasoline and diesel cars at 60 mpg instead of 30 mpg (or, at 30 mpg, going 6,000 rather than 12,000 miles per year).	Lifestyle (car size and power) Urban design

Reductions, for tough limits, by 2050 = ~ 6 Gt(C)/yr

Achieving stabilization, slice by slice (p.2 of 2)

Mitigation	1 Gt(C)/yr Global Business	Risk, Impact
Geological seq'n	3500 Sleipners, at 1 Mt(CO_2)/year	Global and local leakage
Land sink	Now 1.5 Gt(C)/yr, sink becomes 2.0 Gt(C)/yr, rather than 1.0 Gt(C)/yr	Current estimate for 2050 sink is *several* times more uncertain
Biomass fuels from plantations	100×10^6 ha, growing @ 10 t(C)/ha-yr	Biodiversity, competing land use (200×10^6 ha = US agricultural area)
Storage in new forest	500×10^6 ha, growing @ 2 t(C)/ha-yr	Biodiversity, competing land use

Reductions, for tough limits, by 2050 = ~ 6 Gt(C)/yr

Examples of "solution science"

Technological solution	**Environmental issues at scale-up**	**Enabling science**
Renewable electricity	Wind and regional climate Albedo modification	PV thin films
Biofuels	Residues: Nutrient needs of soils Plantations: air emissions	Genomics for H_2 from H_2O
Fossil carbon capture/storage	CO_2 leakage from aquifers Deep ocean CO_2 retention	H_2 production, storage, safety, use Co-capture, co-storage (e.g., C + S) Mining, reactivity of silicates
Unconventional hydrocarbons	Methane clathrate stability	Clathrate physical chemistry
Nuclear energy	Uranium from seawater	Non-proliferation: Pu, U^{235} enrichment Fusion, fusion-fission hybrids
Direct capture of CO_2 *from air*	Regional climate	Absorbers

Unsolicited advice #4

Deepen our understanding of “slices.”

Specifically, pursue “solution science." That is, address the feasibility, risks, and costs of technological "solutions" that mitigate climate change at significant scale.

Summary of Unsolicited Advice

1. Incorporate environmental science into your research program.

2. Give a prominent role to hydrogen production from fossil fuels with CO_2 capture.

3. Investigate materials, catalysts, and sensors that can improve hydrogen production from fossil fuels. Investigate retail delivery of hydrogen and hydrogen safety.

4. Deepen our understanding of the feasibility, risks, and costs of technological "solutions" that mitigate climate change at significant scale.

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