Slices and Wedges: Useful Words to Describe the Daunting Challenge of Managing Global Carbon

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BP Sunbury
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Outline of Talk

I. Introduction to the Carbon Mitigation Initiative (CMI)
II. The Stabilization Wedge
III. The Wedge Game
IV. Slices: The Unit of Action

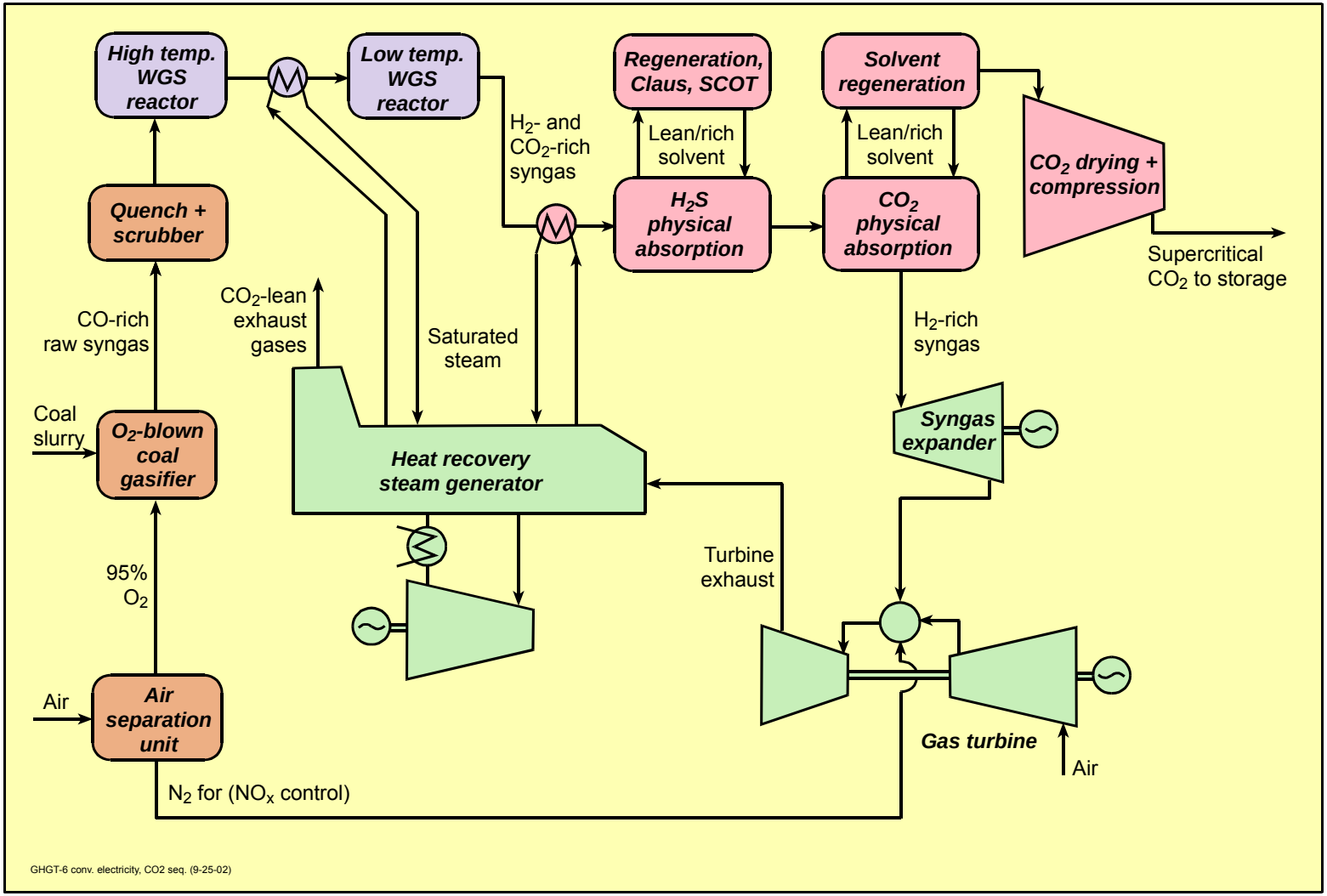
CMI Mission Statement

The vision of the CMI is to lead the way to a compelling and sustainable solution of the carbon and climate change problem. By combining the unique and complementary strengths of the CMI parties — one premier academic institution and two influential global companies —CMI participants seek to attain a novel synergy across fundamental science, technology development, and business principles that accelerates the pace from discovery, through proof of concept, to scalable application.

Carbon Mitigation Initiative at Princeton, 2001-2010

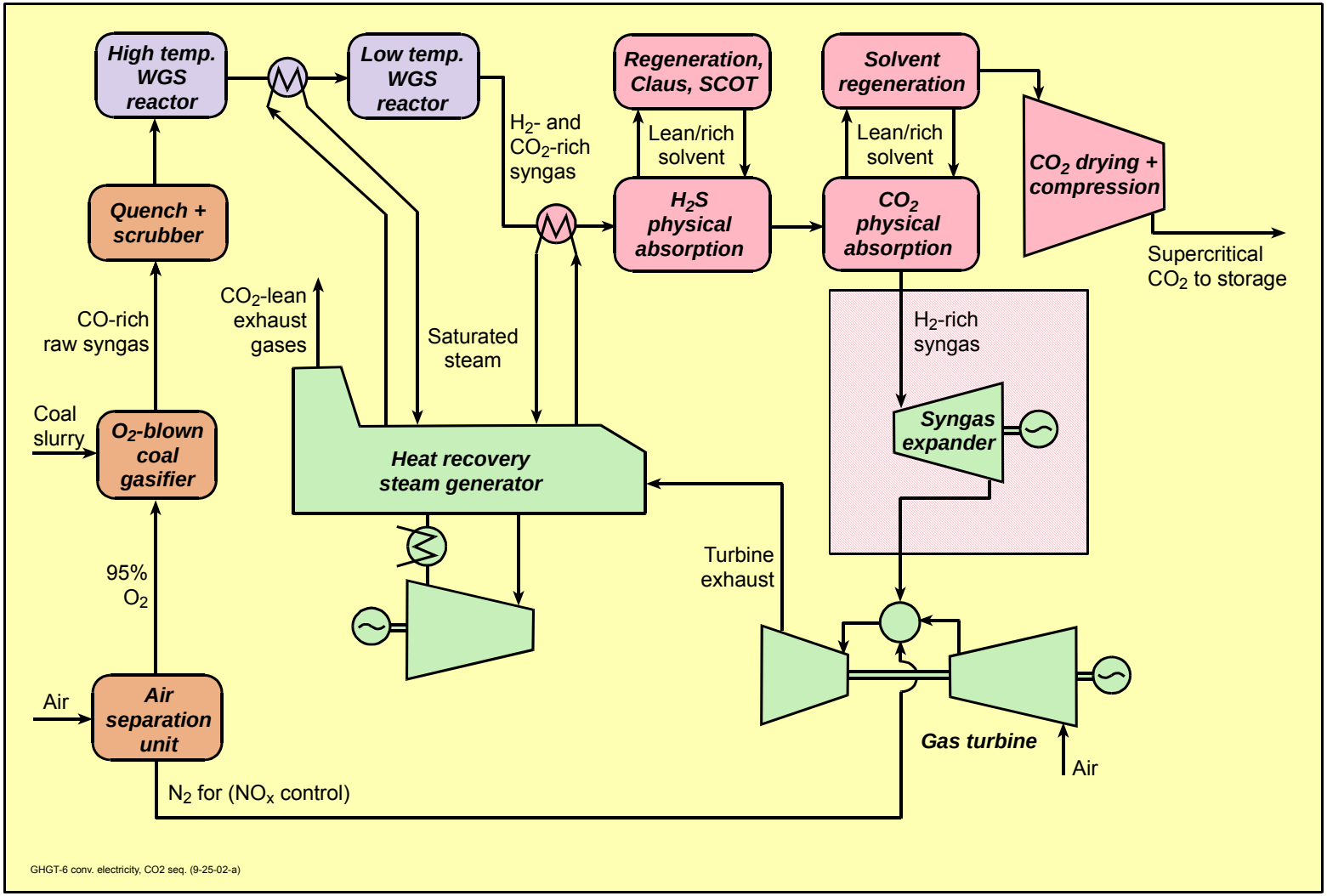
$21,150,000 funding from BP and Ford.

Benchmark: IGCC Electricity with CO_2 Capture



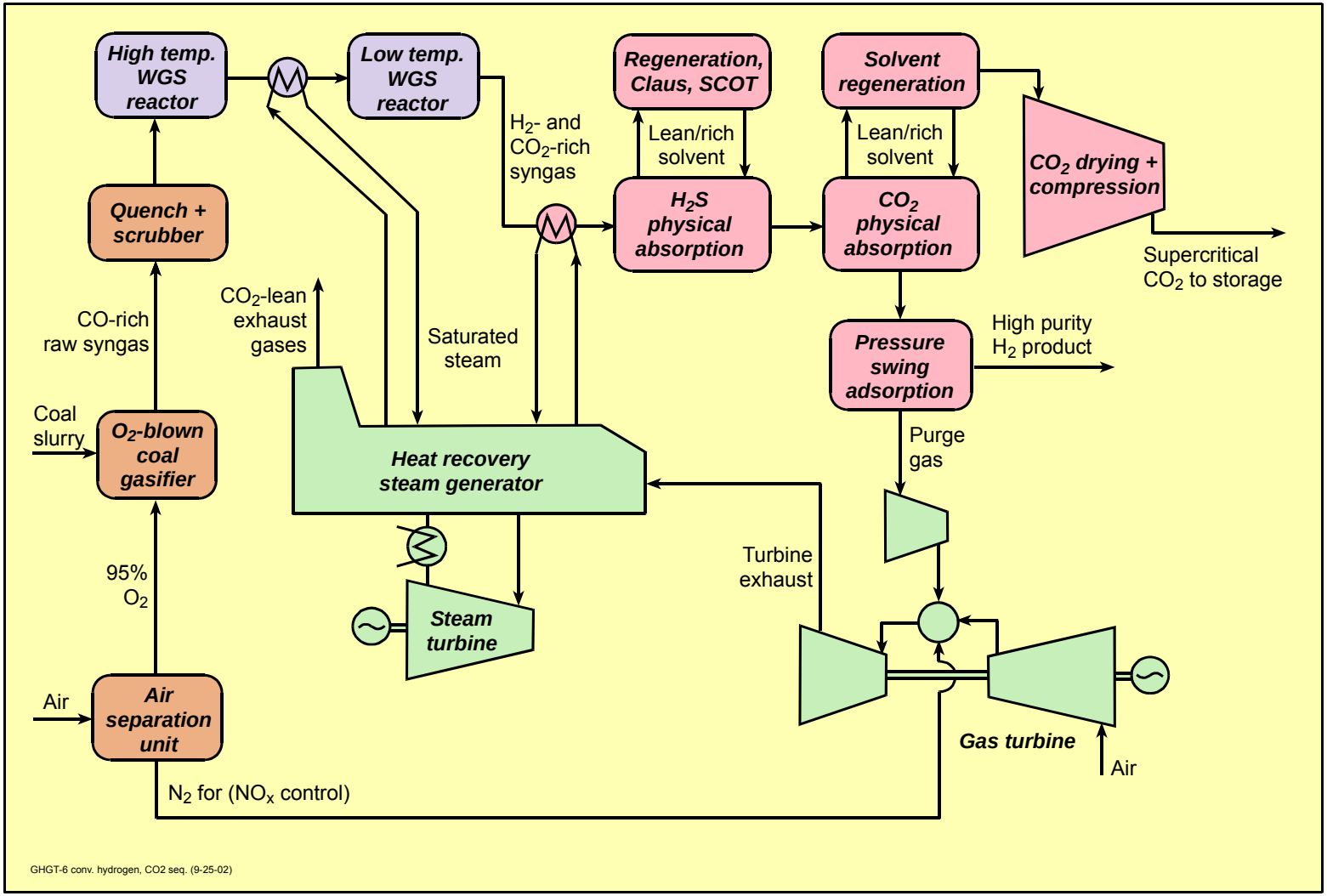
- Cost: 6.4 ¢/kWh (at carbon tax of 93 $/tonne C), efficiency: 34.8% (HHV). (70 bar gasifier with quench cooling; plant scale: 368 MW_e)

H_2 Production: Add H_2 Purification/Separation



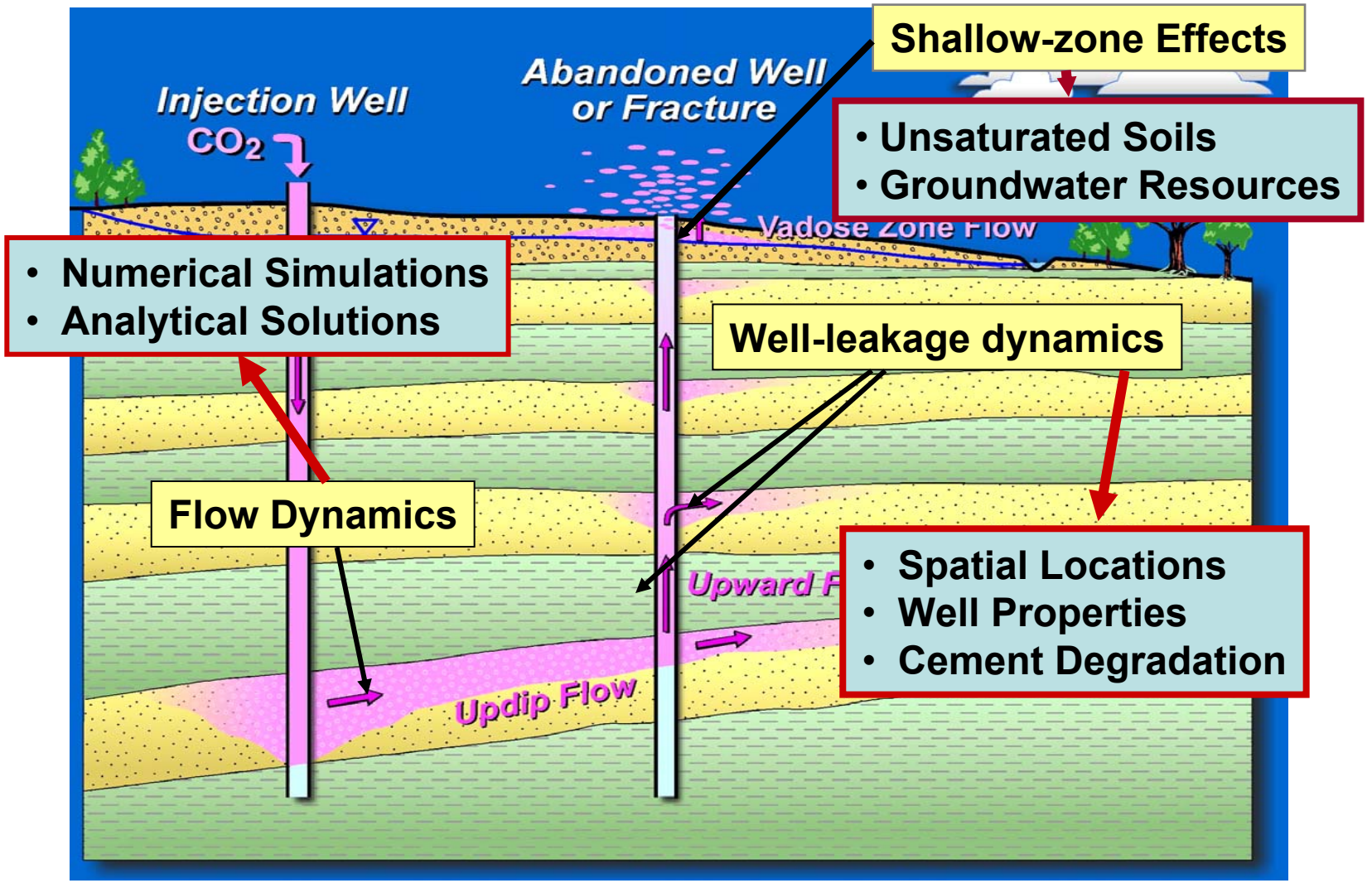
- Replace syngas expander with PSA and purge gas compressor.

Conventional H_2 Production with CO_2 Capture

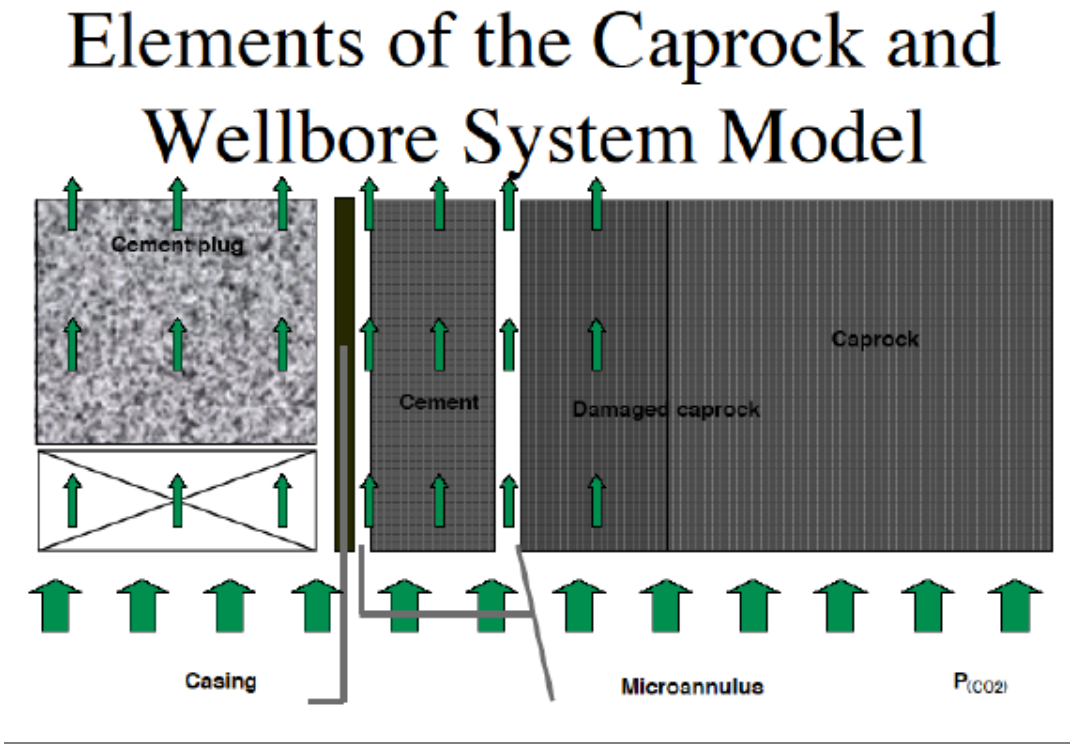


- H_2 cost: 7.5 $/GJ (HHV) (at carbon tax of 38 $/tonne C, electricity 4.6 ¢/kWh). [70 bar gasifier with quench cooling; plant scale: 1210 MW_{th} H_2 (HHV)]

CO_2 Injection and Leakage Pathways



Potential Leakage Paths



Flow through cement or cap rock insignificant

Critical paths:

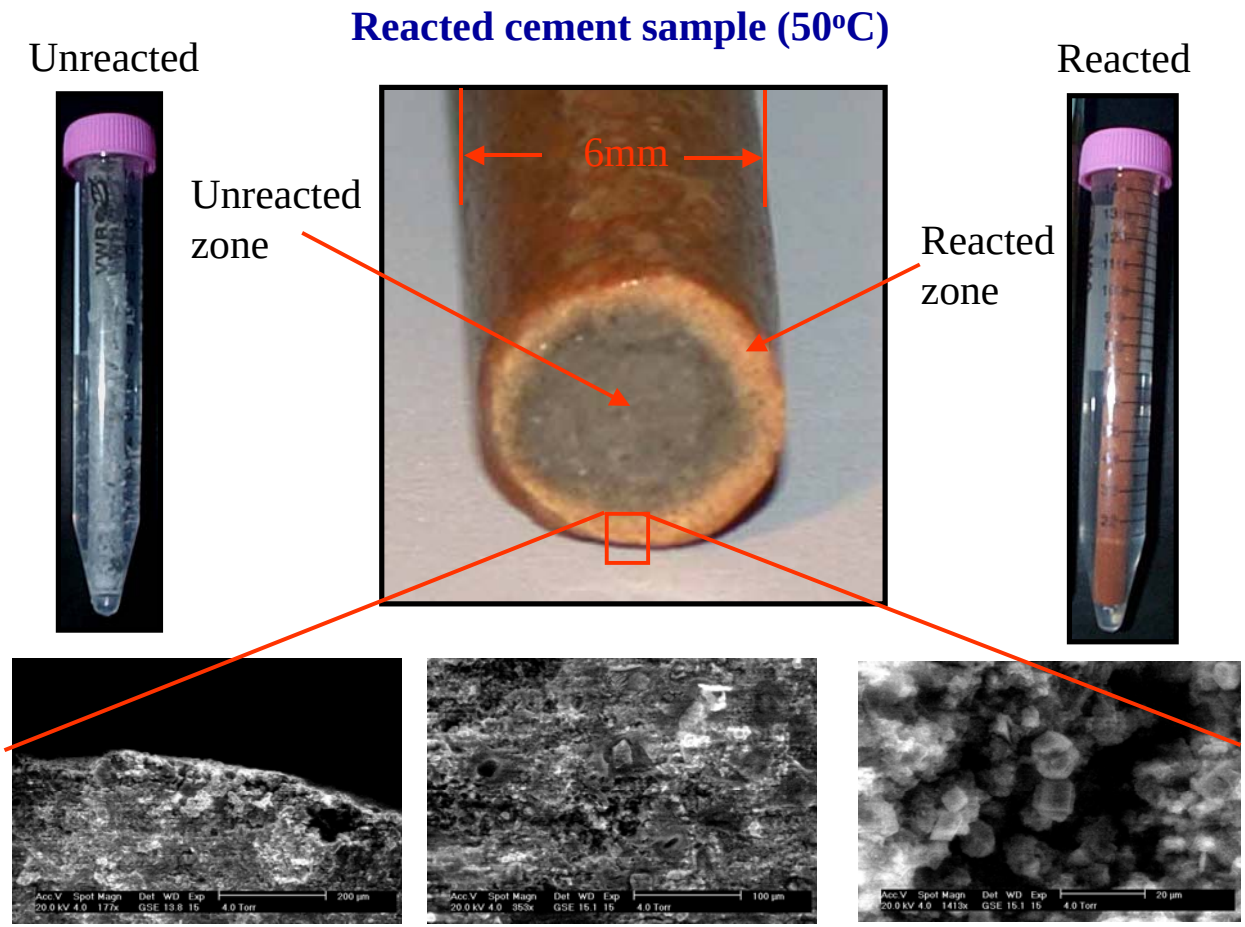
Existing annuli between cement & casing or cap rock

Existing zone of damaged cap rock

Dissolution of cement by flow through annuli or damaged cap rock

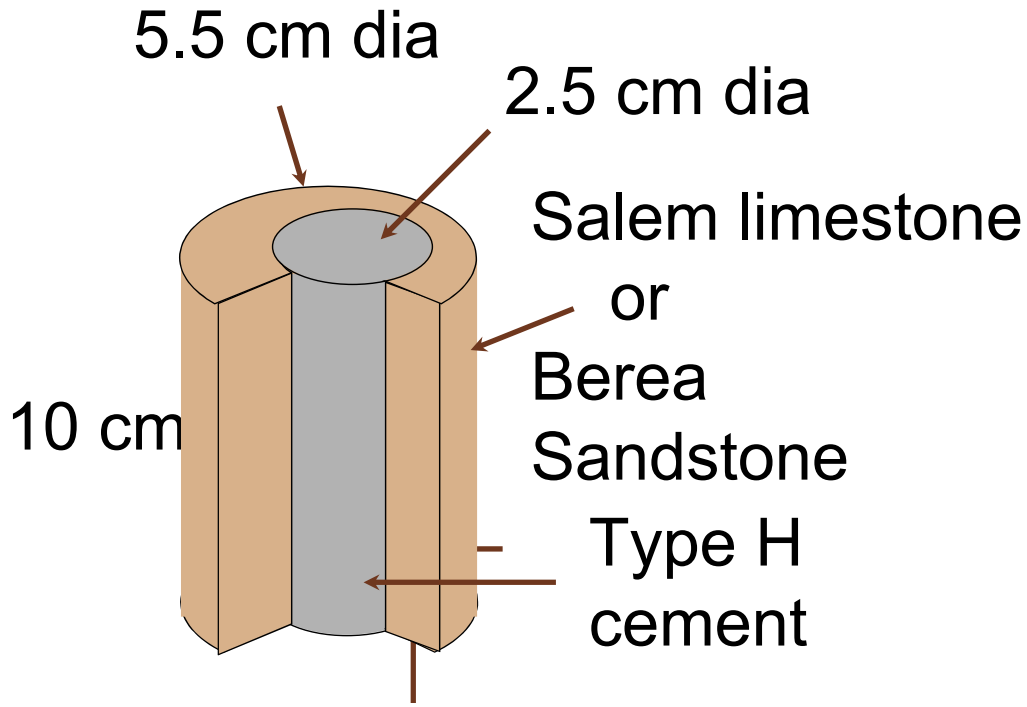
From *Canadian CO_2 Capture and Storage Roadmap Strawdog*, Bill Gunter, Alberta Research Council

Corrosion of Cement in Carbonated Brine

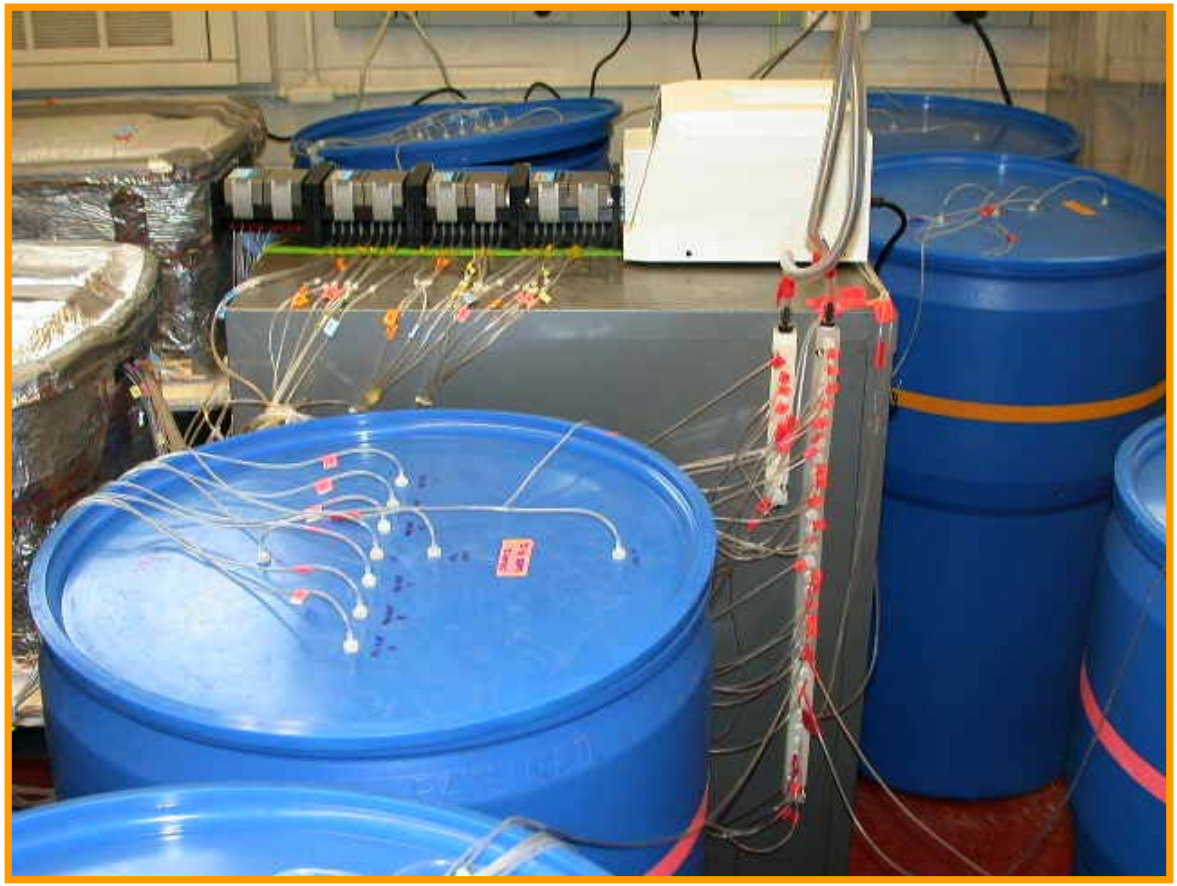


Stone/Cement Composite Samples

- Cement with additions of 0, 6, 12 % bentonite
- Typical formation stones
- Cement core off - center to vary diffusion distance



Low-*P* Experiment



Tanks of carbonated brine

RMOTC Collaboration

- Plans are underway to acquire samples of cement from old wells
- We will attempt to retrieve the cement/formation interface
- Results will reveal initial condition of cement
- Test samples will be prepared to replicate existing properties

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Lord Browne Nov 25, 2003

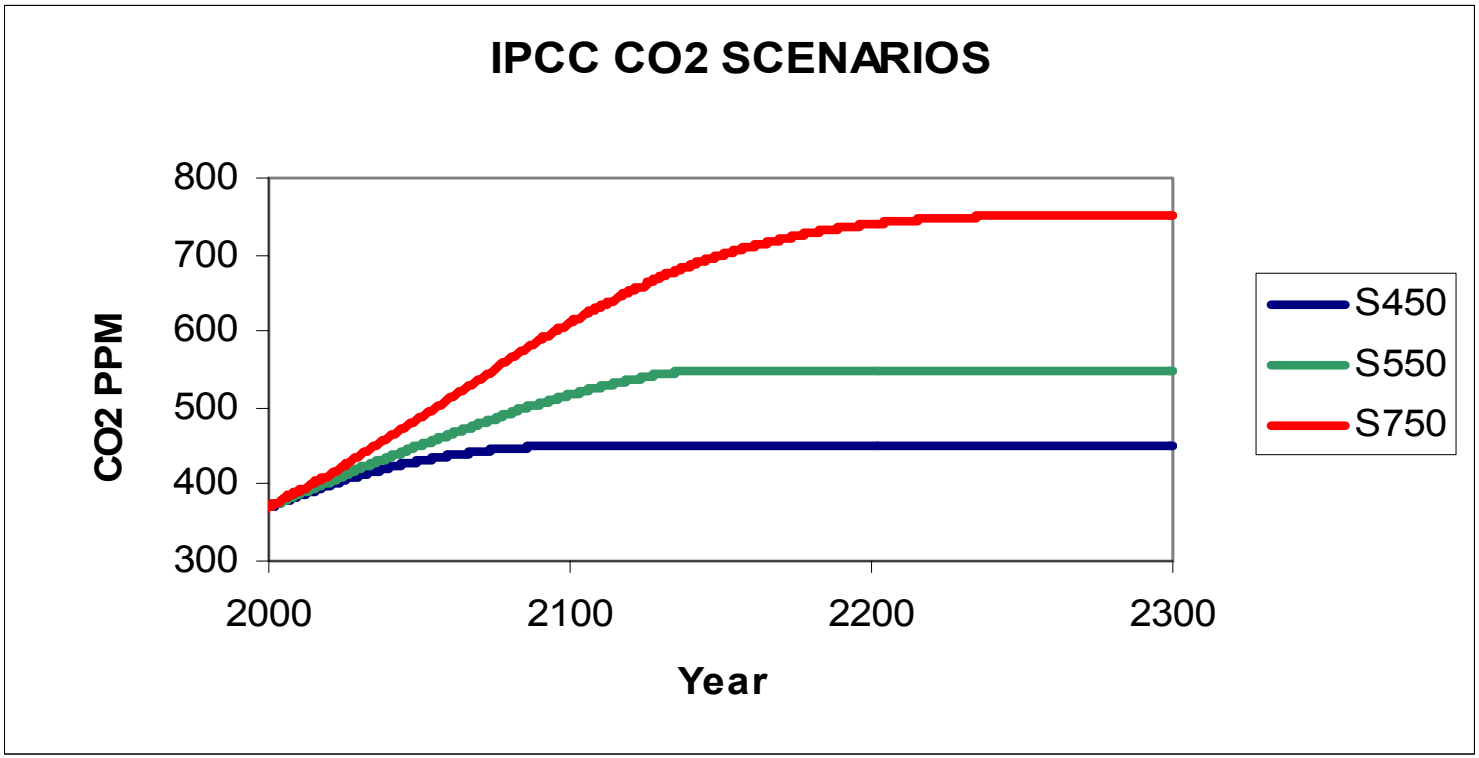
"Based on our understanding of the range of uncertainty around the scientific views, we've come to the judgment that to avoid serious impact upon societies or the environment, it is necessary to stabilize atmospheric concentrations of greenhouse gases at around 500-500 parts per million."

"Such a shift to a significantly lower carbon economy would require the removal by 2050 of a significant volume of carbon emissions."

"There is no single solution – no magic bullet. But on the basis of practical steps, using technology which is either available [or] which may be within reach, stabilization on that timescale does seem to be an attainable goal.

"Some very interesting work done at Princeton University…

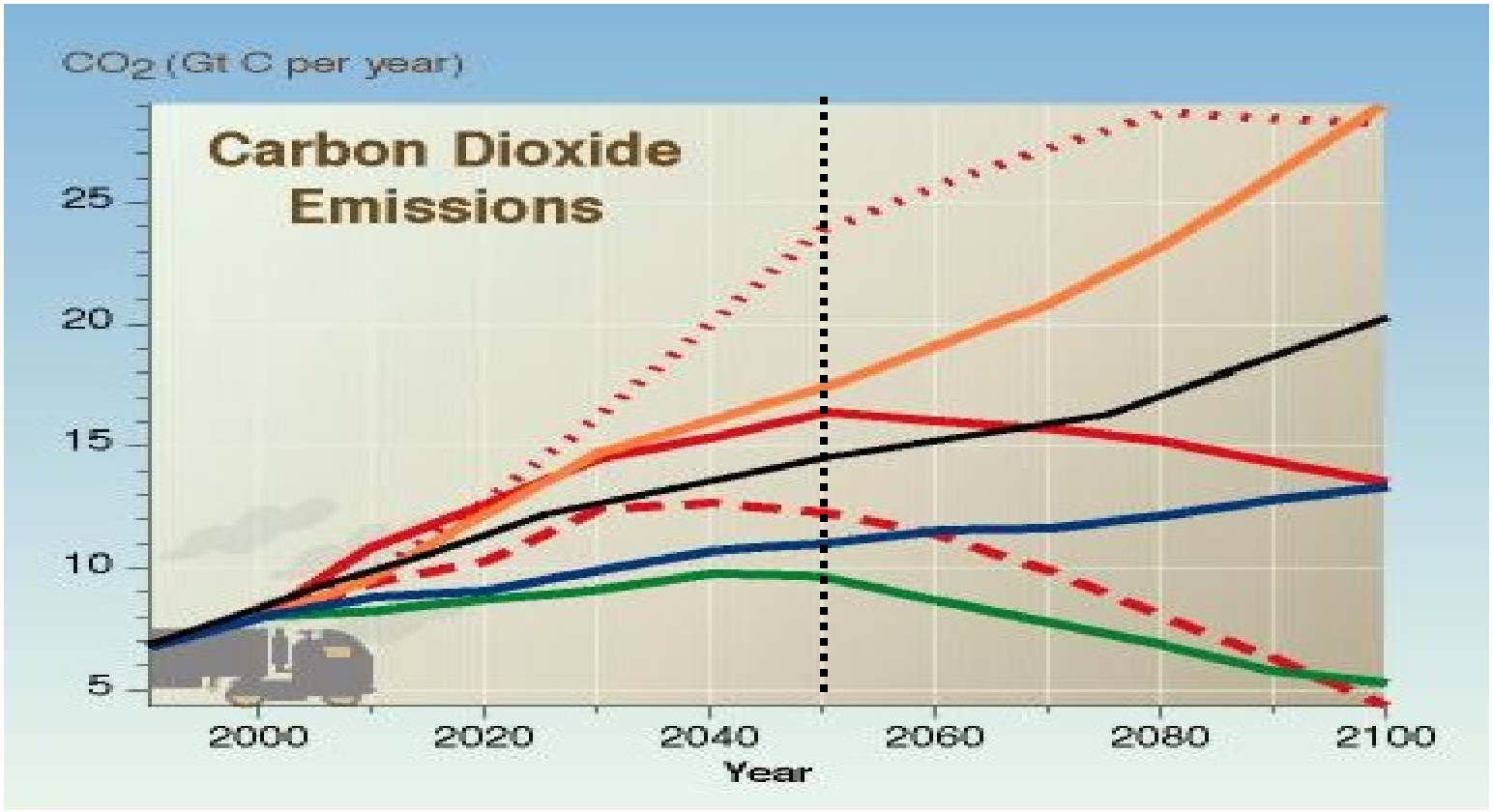
The Goal: Getting to What?



The graph presumes “Stabilization” and focuses on the choice of target. But the eye moves to “2300,” and the impetus to action is desensitized. Moreover, the first quarter century is a blur.

The Baseline: Starting from Where?

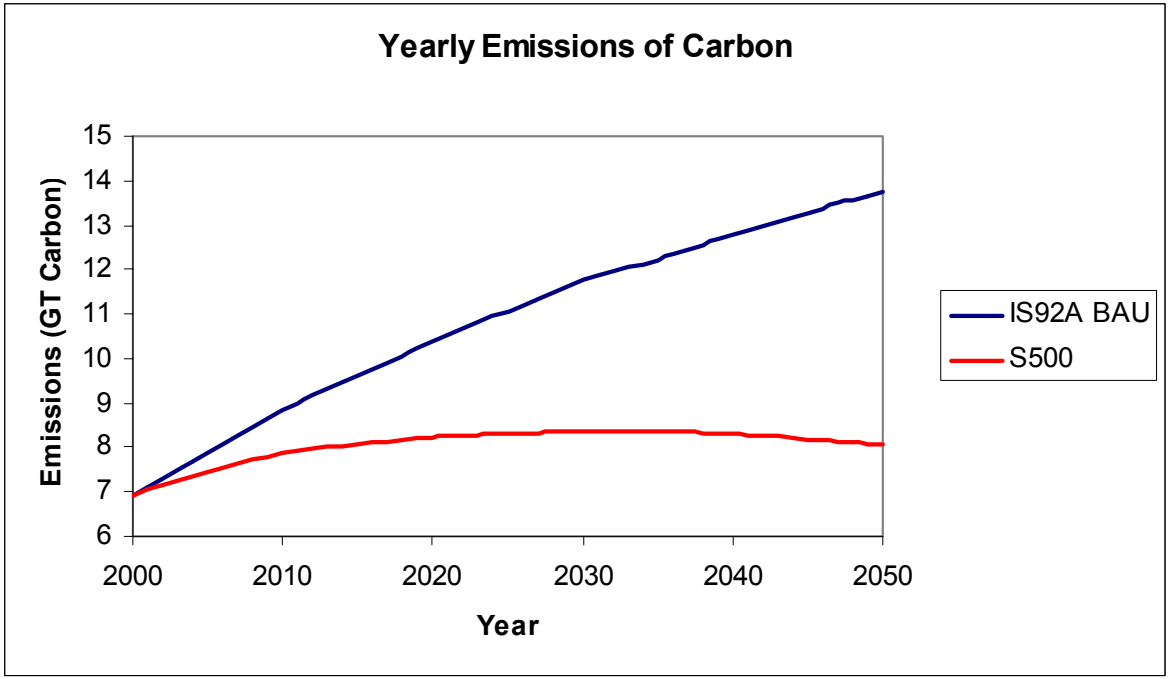
The IPCC Emissions Scenarios



"Baseline" emissions in 2050 are up for grabs: 10-24 GtC/yr (1½ – 3½ x present day).
By stressing the unknowable consequences of inaction, the impetus to action is reduced.

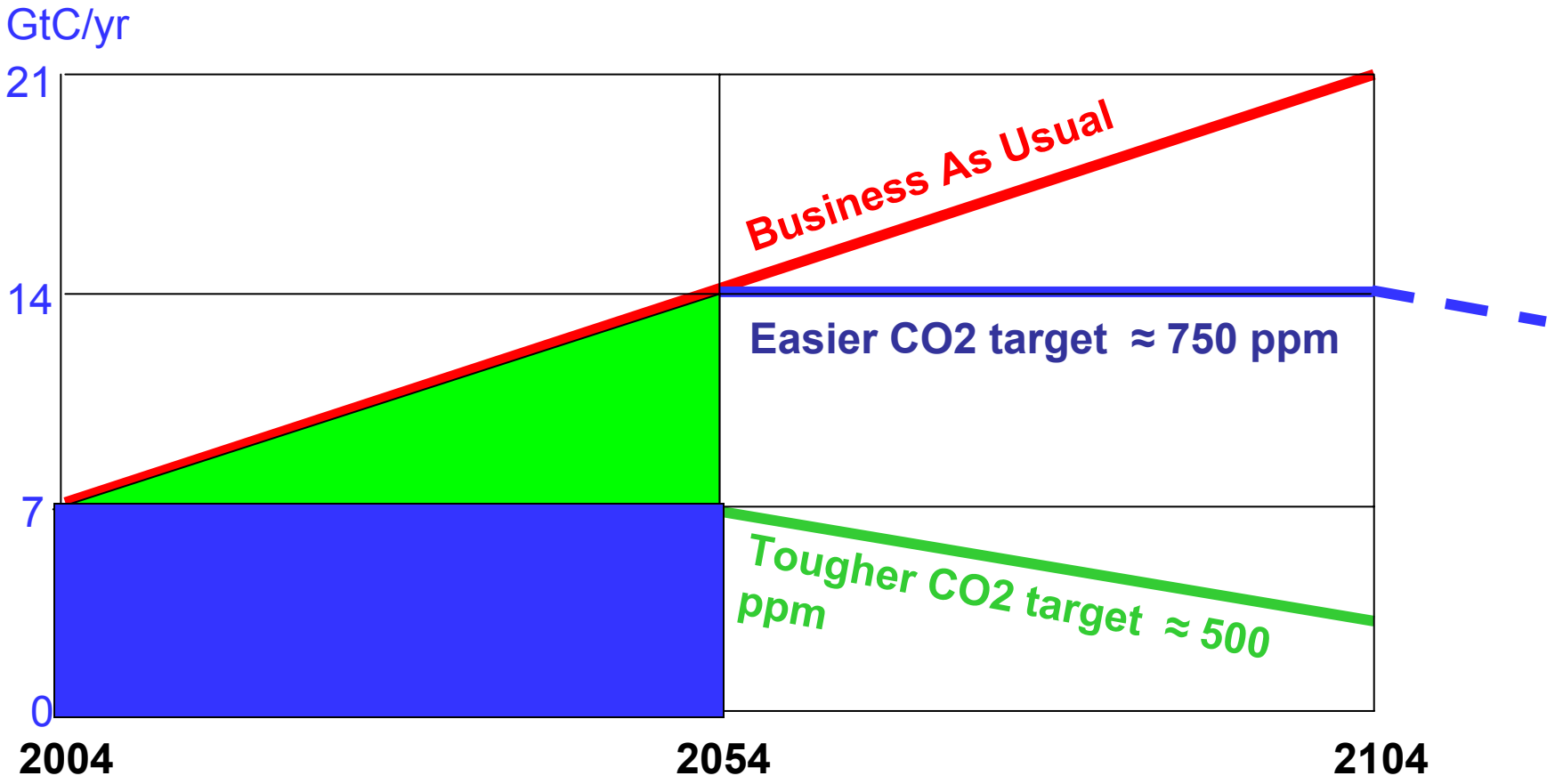
From Multiple Targets and Baselines to The Stabilization Wedge in Three Steps

Step One: Restrict attention to 50 years (the Goldilocks time frame)
Step Two: Choose just one goal and one baseline

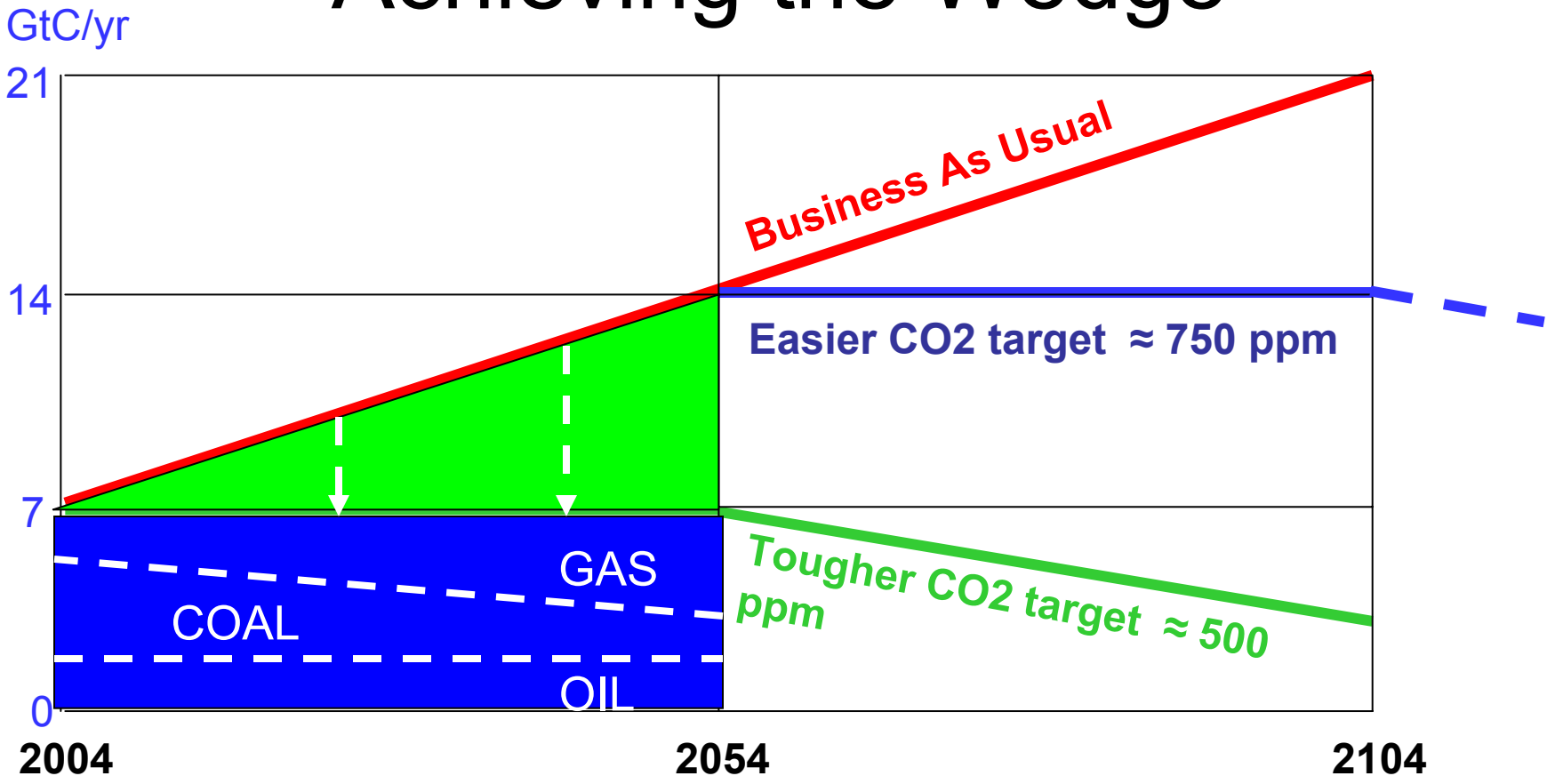


Step Three: Abstracting further, take the goal to be flat emissions and the baseline to be doubling linearly in 50 years.

The Stabilization Wedge



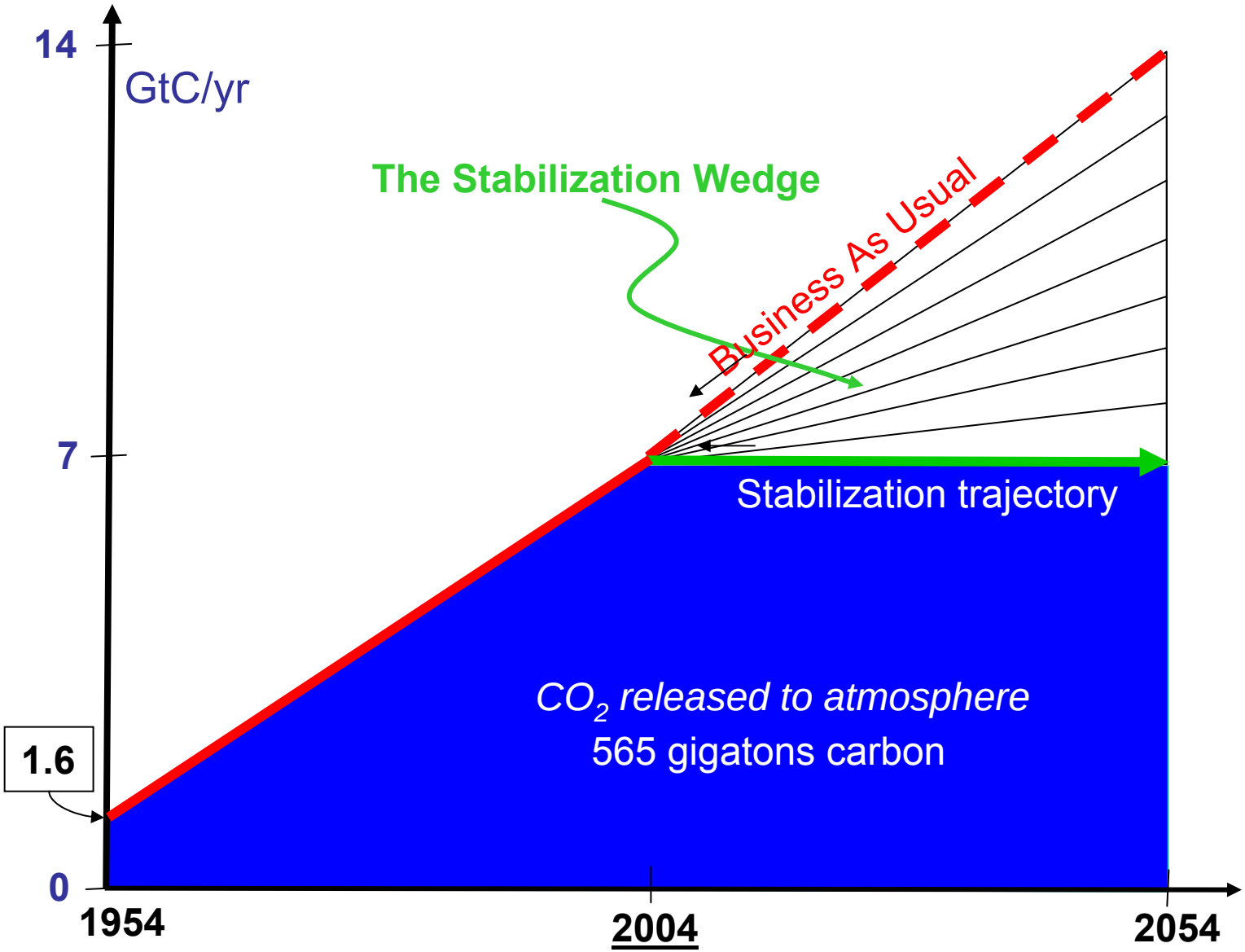
Achieving the Wedge



2000 (IEA): Gas 1.3 GtC/y; Oil 3.0 GtC/y, Coal 2.5 GtC/y:

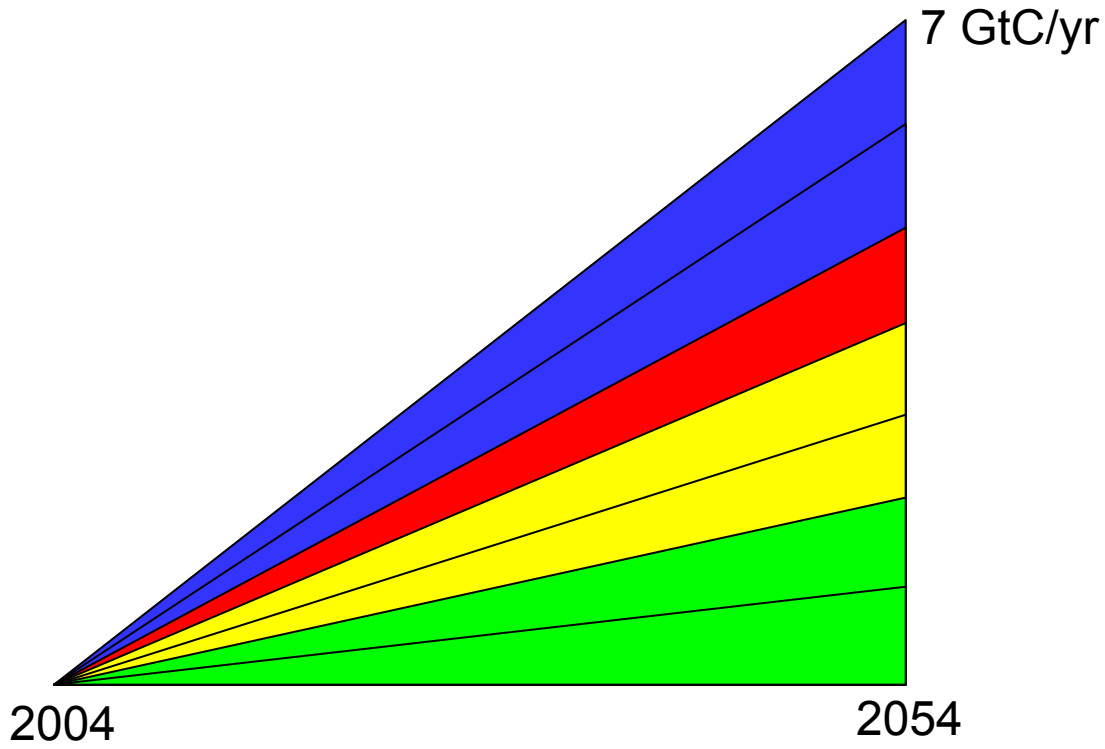
Achieving the wedge will probably mean that gas's share of the constant total CO_2 emissions will grow relative to coal's. Coal's share of *energy* depends on whether CO_2 from coal is captured and stored.

50 Years Back, 50 Years Forward



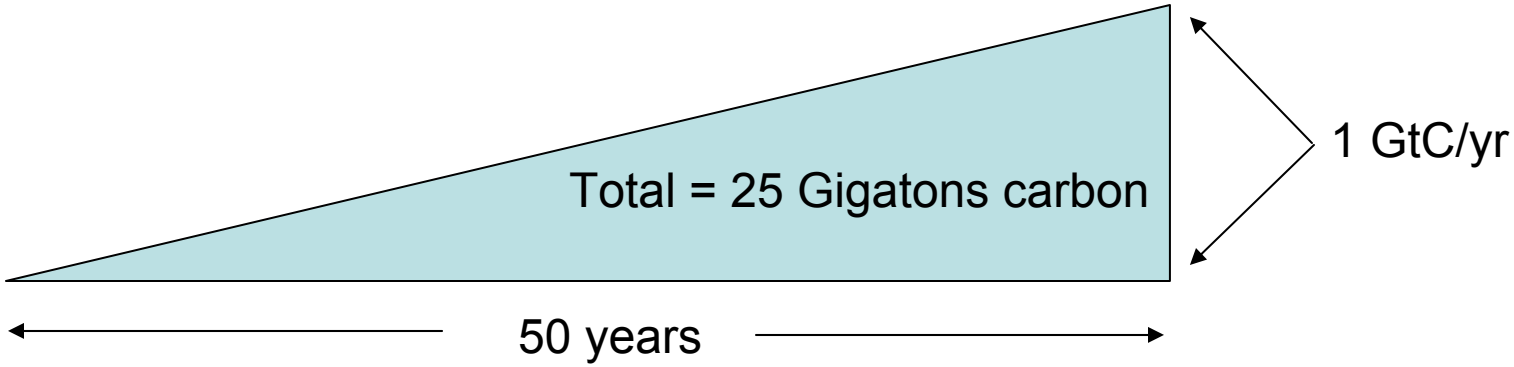
Seven “Slices” Fills the Wedge

It is irresistible to divide the wedge into seven equal parts. We call these “slices.”



What is a “slice”?

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



Cumulatively, a slice redirects the flow of 25 Gt(C) in its first 50 years. This is 2.5 trillion dollars at $100/t(C).

A “solution” to the Greenhouse problem should have the potential to provide at least one slice.

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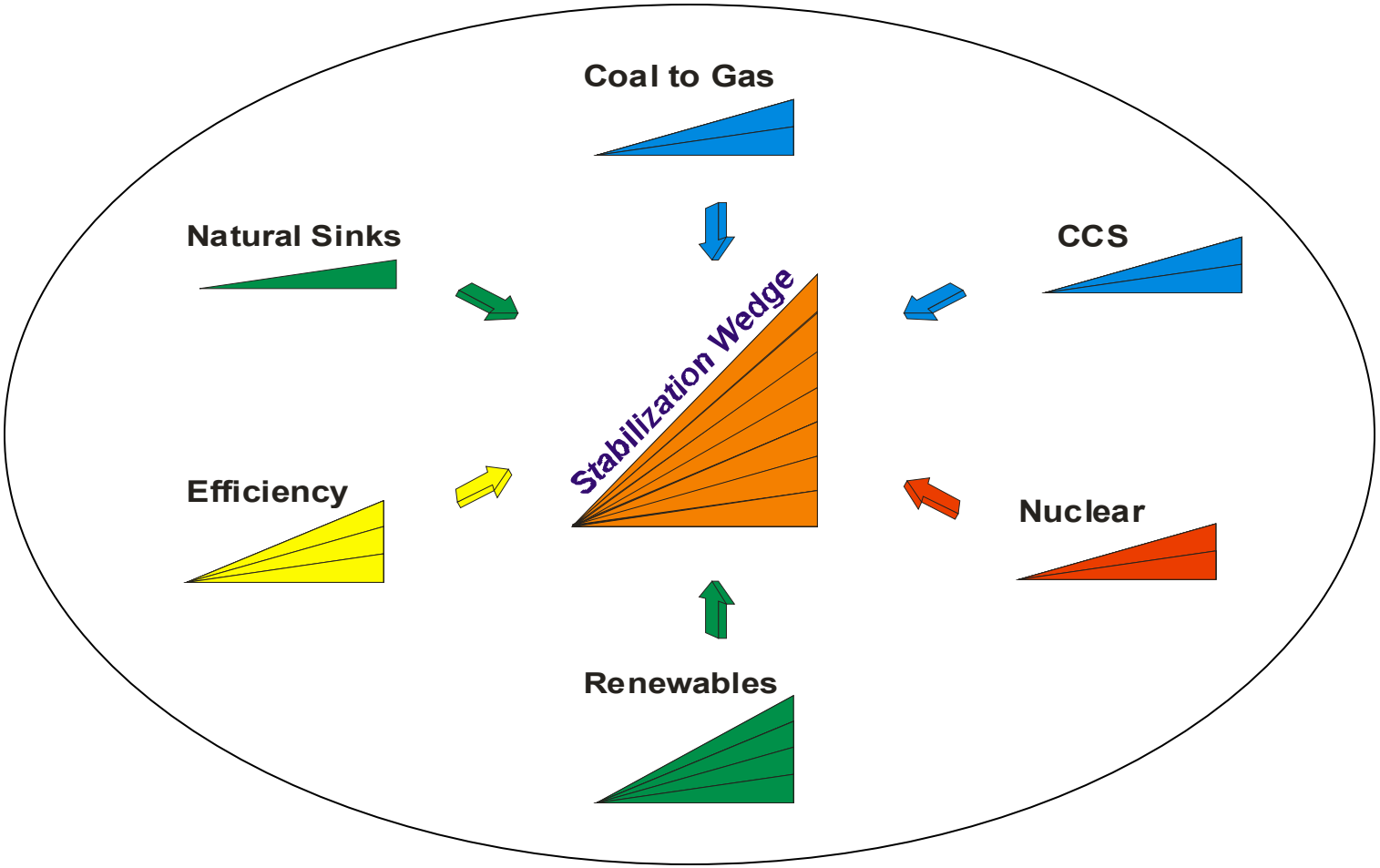
Filling the Wedge

The strategies available to provide the slices to fill the wedge are grouped below. All strategies are based on technologies already in use.




Heat Eff.
Transport. Eff.
Nuclear Elec.

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Business As Usual

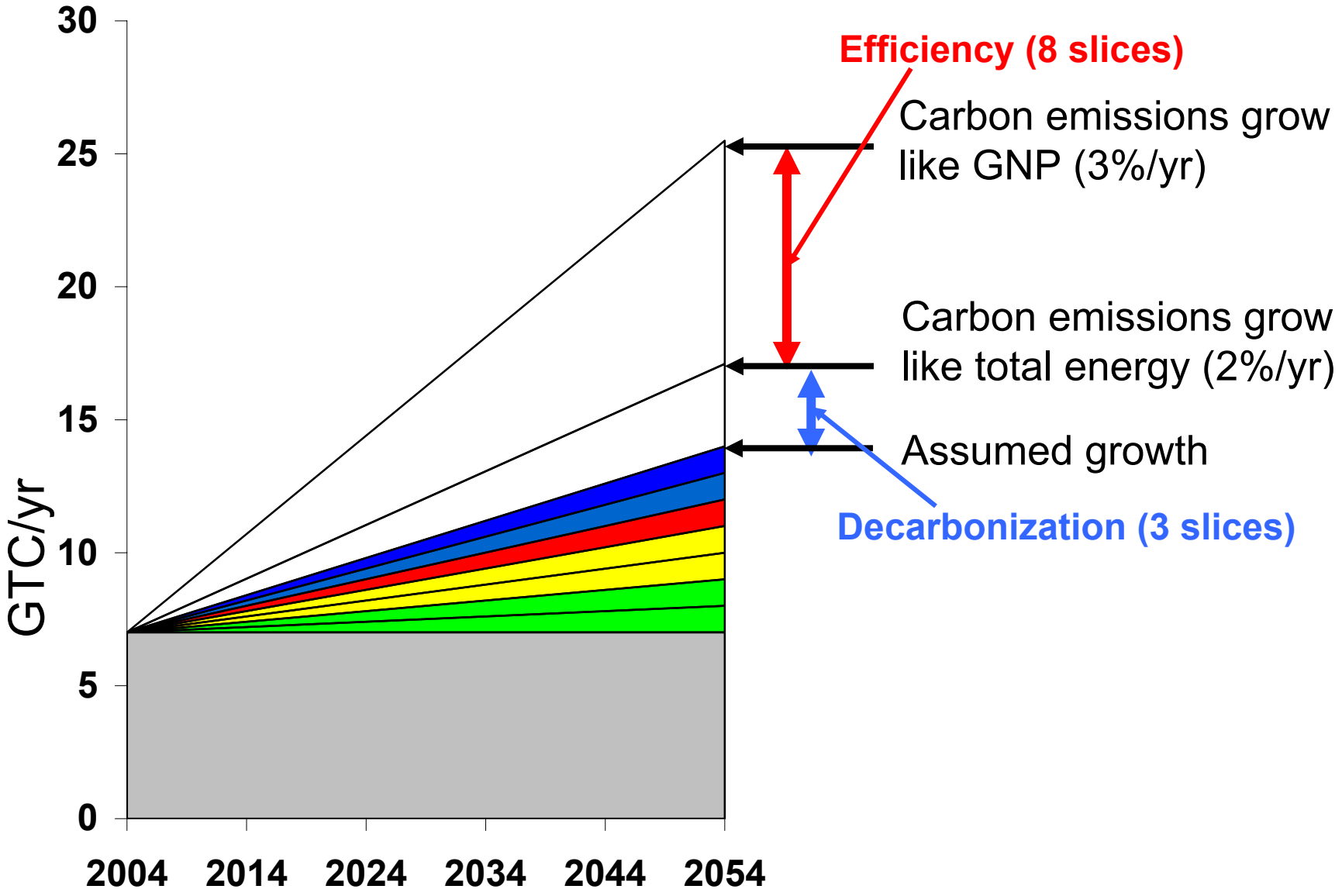
Our Business As Usual (BAU) emissions trajectory, intersecting 14 GtC/y in 2050, is at the center of many clouds of estimates.

Most specific BAU trajectories “use up” a few of the slices we discuss here.

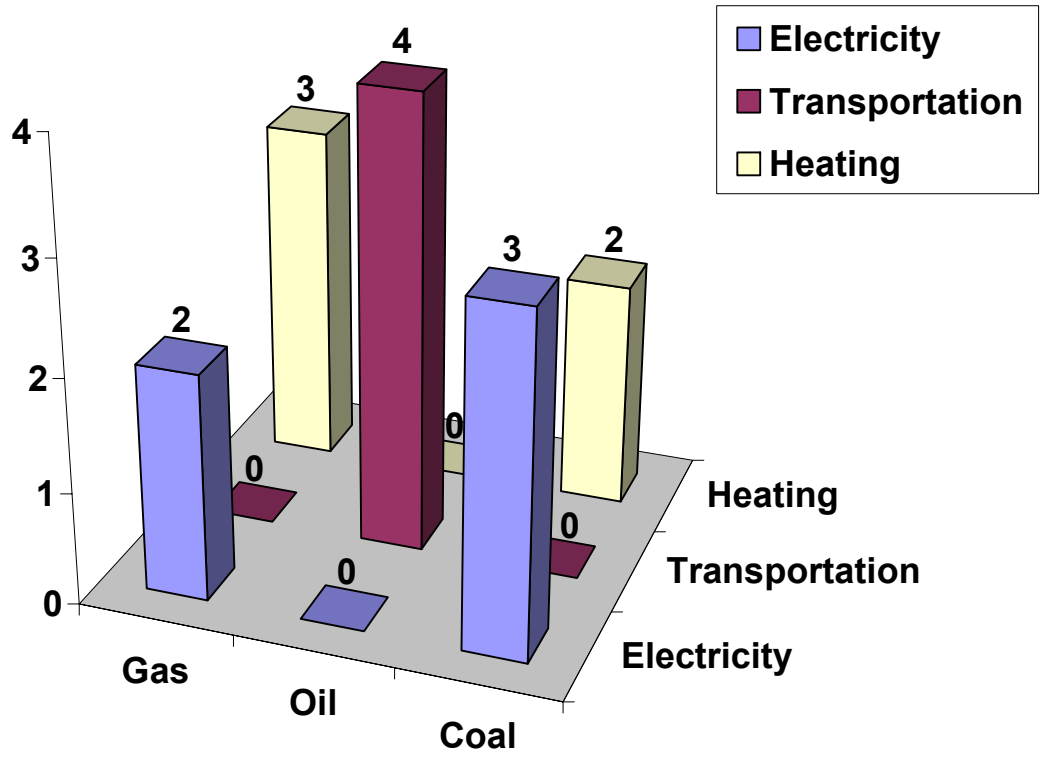
Stay focused on comparing two “stories”:

1. the world is oblivious to carbon management (BAU)
2. the world is investing heavily in carbon management

Efficiency and Decarbonization



Fuel Sources for 14 GtC/y in 2054

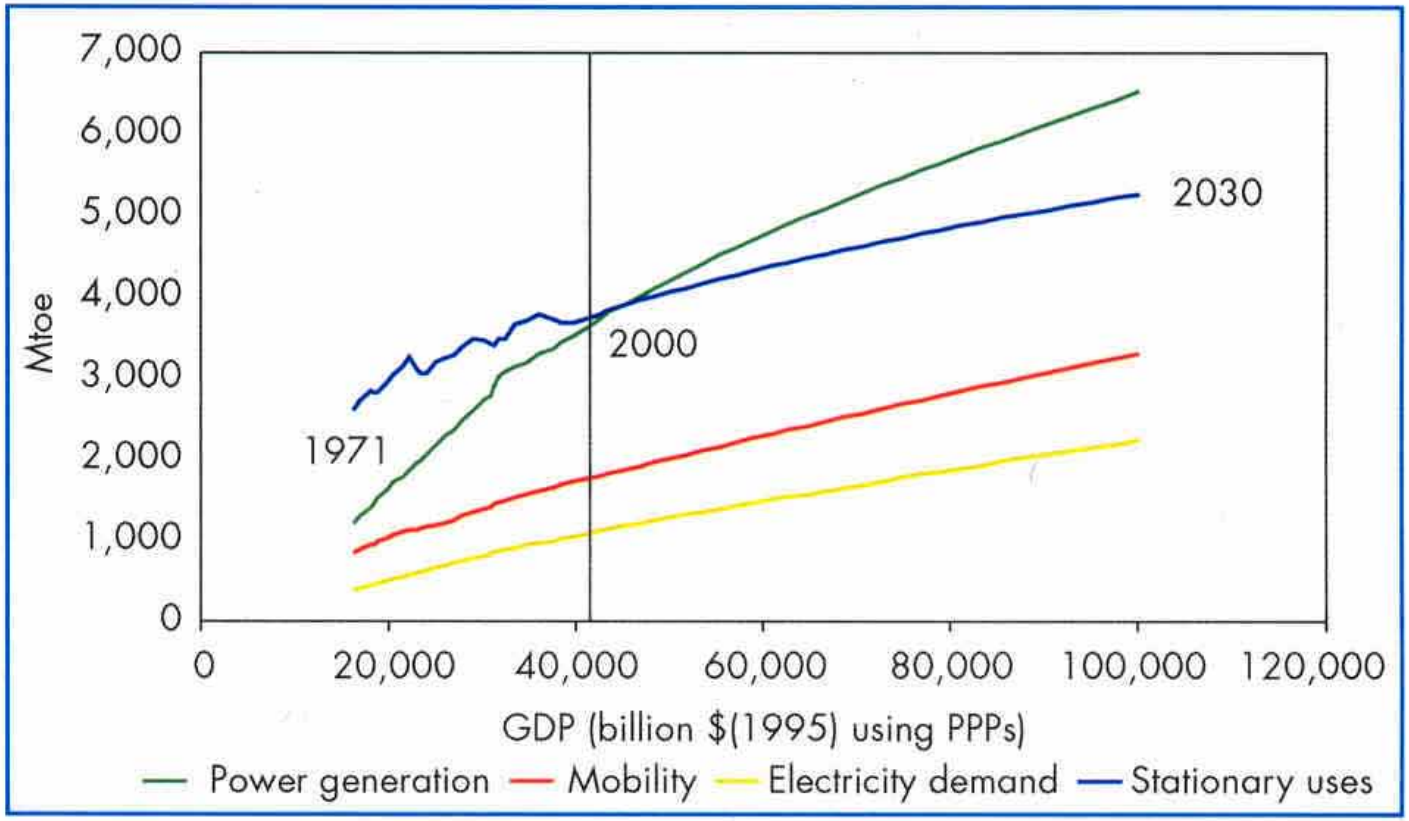


Carbon emissions today arise about equally from providing electricity, transportation, and heat (for industry and buildings). To cut 2054 carbon emissions by half, all three uses must be decarbonized.

Coal and gas compete today in markets for electricity, process heat, and (in developing countries) space heat. Coal dominates the electricity market.

The Three "End Uses"

Figure 2.6: **World Energy-Related Services, 1971-2030**



Source: *World Energy Outlook, 2002.* IEA

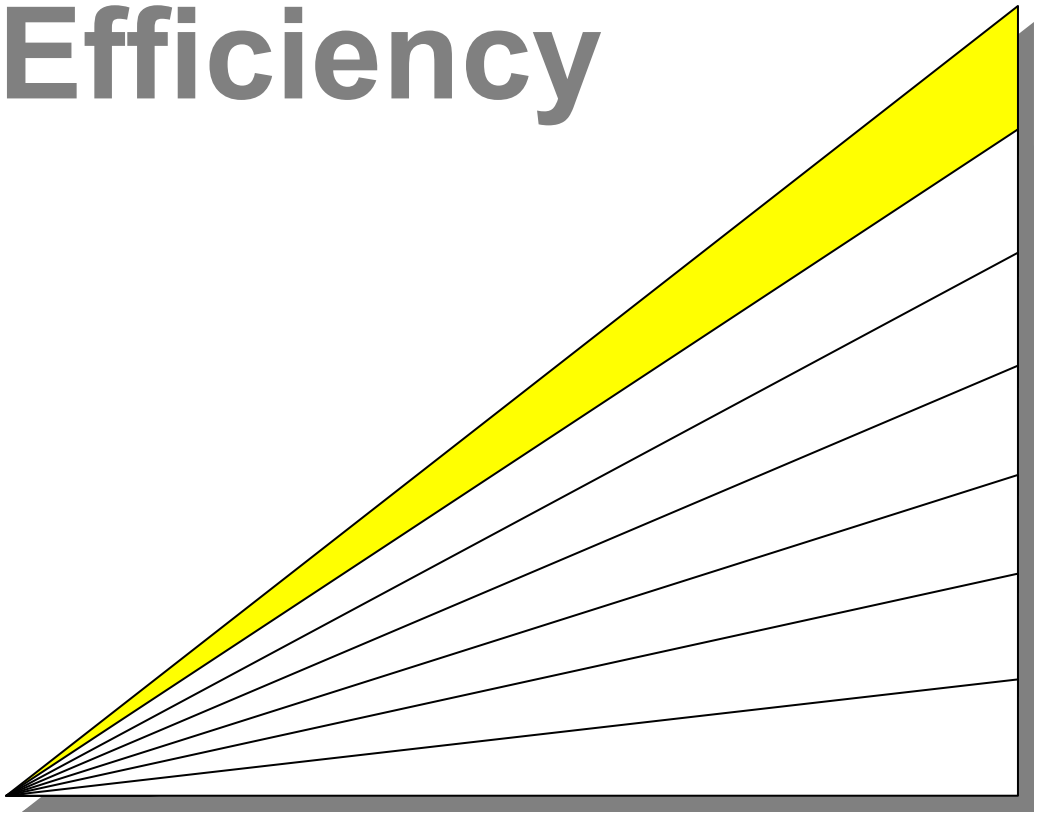
Double-counting

One can displace the emissions of a coal-based power plant only once!

- As carbon mitigation strategies, displacing a coal plant with a natural-gas-fired plant, a nuclear plant, and a windfarm compete with one another, *and* with capturing and storing the coal plant's CO_2 emissions, *and* with efficient use of electricity (motors, lighting).

Candidates for slices, below, are assumed to be providing the *first* reduction in carbon emissions, i.e., from 14 GtC/y to 13 GtC/y.

Efficiency



Efficiency in transport

Effort needed for 1 slice:
2 billion gasoline and diesel cars (10,000 miles/car-yr) at 60 mpg instead of 30 mpg

500 million cars now.

ng Organization

Potential Pitfall:

Suburban sprawl

Efficiency in buildings

Effort needed for 1 slice:

Targets: Space and water heating (passive solar, heat pumps) ; lighting; appliances.

1/3 slice: All vs half of 50 billion light fixtures have compact fluourescent bulbs (10kgC/yr saved per fixture), present C-intensity of electricity.

Potential Pitfalls:

Air conditioning in tropics

House size

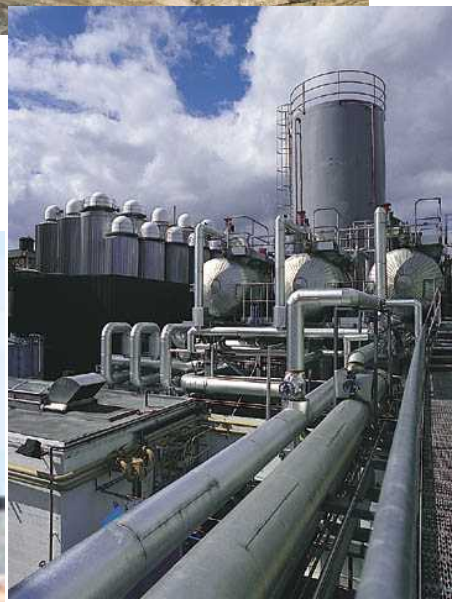
Graphics courtesy of General Electric, DOE, LBNL,Baldor Electric Co.

Efficiency upstream

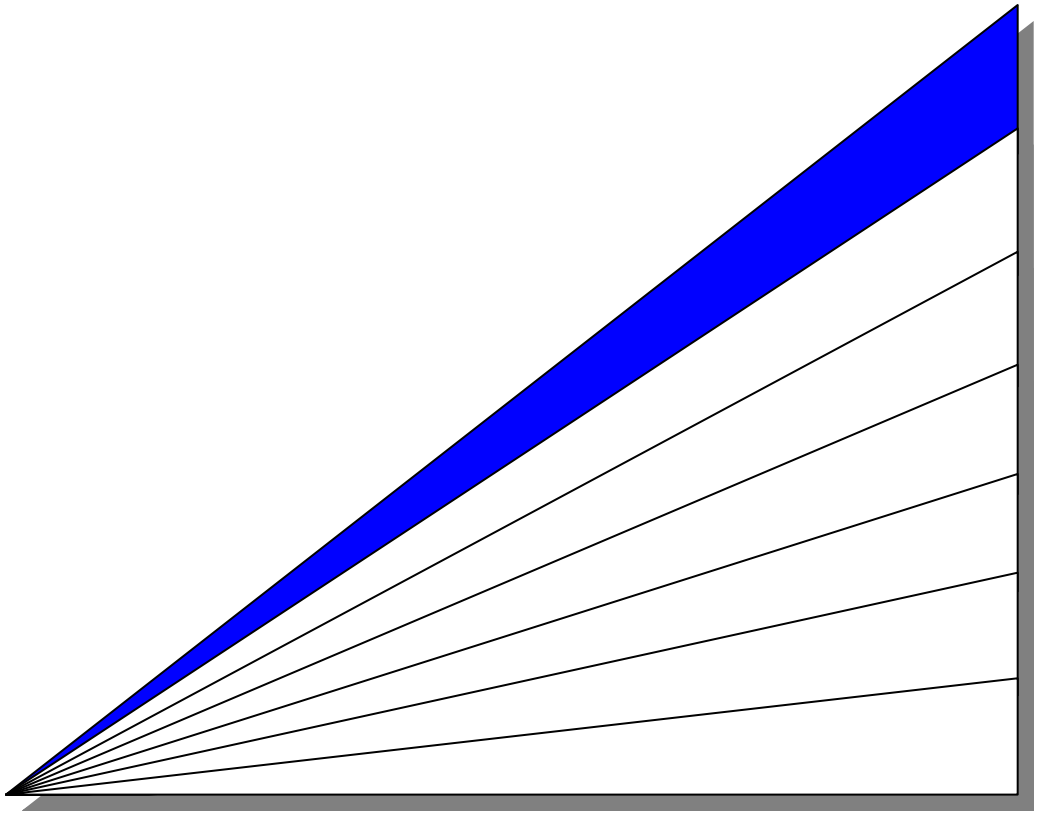
Effort needed for 1 slice:

“Overheads” are 1 GtC/y, not 2 GtC/y, (out of 14 GtC/y) on fuels extraction, processing, distribution (upstream of power plants)

Power plant efficiency is 60%, not 40%. In GtC/y: 2 elec out from 4, not 5, fuel in.



Displace Emissions in Coal Power Plants



Coal to Gas for Electricity

Effort needed for 1 slice:

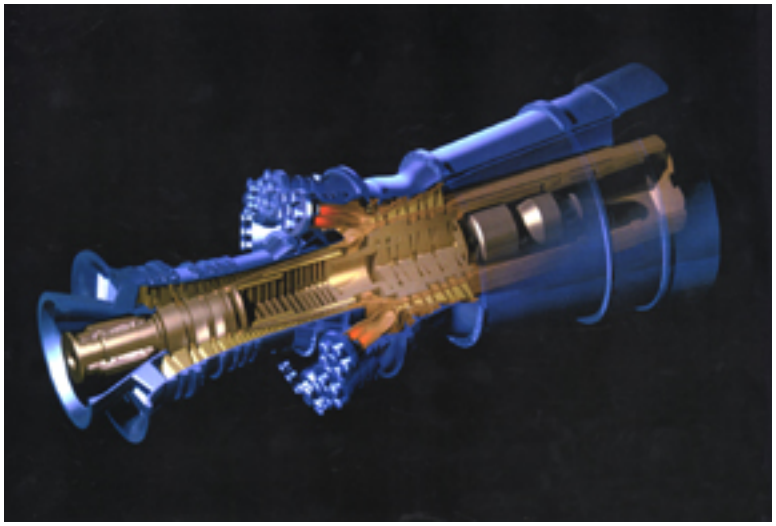
700 1-GW baseload coal plants (5400 TWh/y) emit 1 GtC/y.

Natural gas emits ~1/2 as much CO_2 as coal, per kWh.

So: by 2054, build 1400 GW baseload (**10,800 TWh/y**) fueled by gas, not coal.

Natural gas: 1 GtC/y = 190 Bscfd

So a slice is **50 LNG tanker discharges/day** by 2054 @200,000 m^3/tanker, or **one new "Alaska" pipeline/year** @ 4 Bscfd.



Cross-section of the GE MS9001H Advanced Gas Turbine
Photo courtesy of DOE

Yr 2000 electricity:

Coal : 6000 TWh/y;
Natural gas: 2700 TWh/y.

Potential Pitfalls:

Natural gas geopolitics

*Carbon Capture**

The Wabash River
Coal Gasification Repowering Project

Graphics courtesy of DOE Office of Fossil Energy

*Step One of Carbon Capture and Storage (CCS)

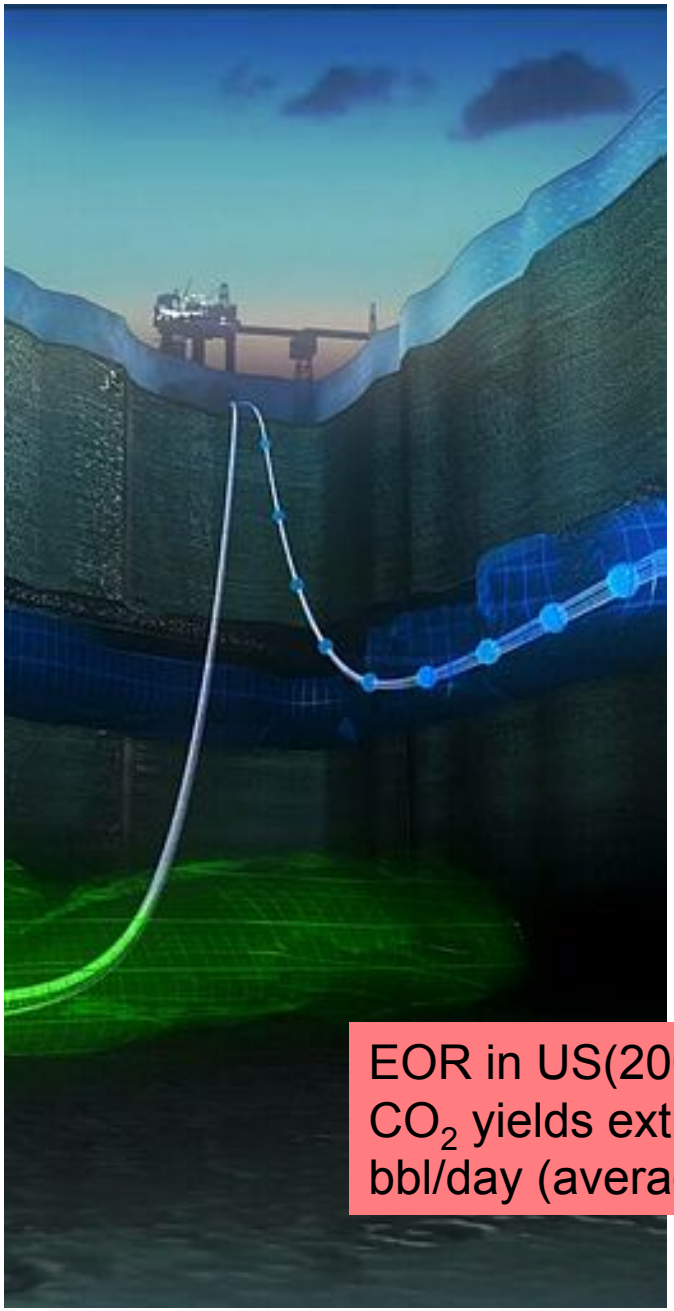
Effort needed for 1 slice:

CCS at 800 GW coal or 1600 GW natural gas, or equivalent H_2 plants.

Potential Pitfalls:

Second step, carbon storage, founders.

Carbon storage



Graphic courtesy of Statoil ASA

Effort needed for 1 slice:

70 Sleipner equivalents (1 Natuna equivalent) installed every year and maintained until 2054

A volumetric flow of supercritical CO_2 somewhat greater than the flow of oil today

Potential Pitfalls:
Public acceptance
Global and local CO_2 leakage

EOR in US(2001): 10 MtC/y as CO_2 yields extra 180,000 bbl/day (average: 7 bbl/tC).

Nuclear Electricity

Graphic courtesy of NRC

Effort needed for 1 slice:

Over 50 years, add 700 GW (twice current capacity): fourteen 1-GW plants/year.

Potential Pitfalls:
Nuclear proliferation and terrorism
Nuclear waste, NIMBY

Plutonium (Pu) production by 2054, if fuel cycles are unchanged: 4000 t Pu (and another 4000 t Pu if current capacity is continued).

Compare with ~ 1000 t Pu in all current spent fuel, ~ 100 t Pu in all U.S. weapons.

5 kg ~ Pu critical mass.

Prototype of 80 m tall Nordex 2,5 MW wind turbine located in Grevenbroich, Germany (Danish Wind Industry Association)

Wind Electricity

Effort needed for 1 slice:

Install 40,000 1 MW_{peak} windmills each year

30,000 MW_{peak} in place today, rate of production growing 30%/yr

60 million hectares (7% of U.S.): multiple use

Potential Pitfalls:
NIMBY
Changes in regional climate?

Solar Electricity

Graphics courtesy of DOE Photovoltaics Program

Effort needed for 1 slice:

Install 40 GW_{peak} each year

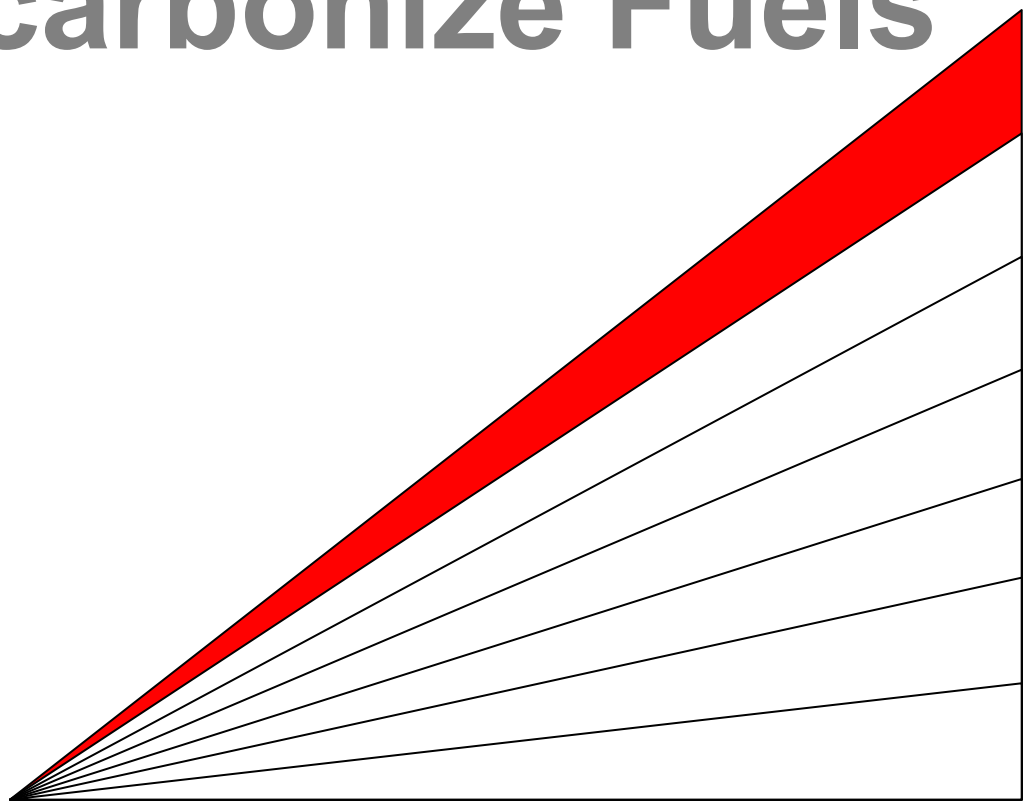
2 GWpeak in place today, rate of production growing 30%/yr

2 million hectares dedicated use by 2054

Potential Pitfalls:

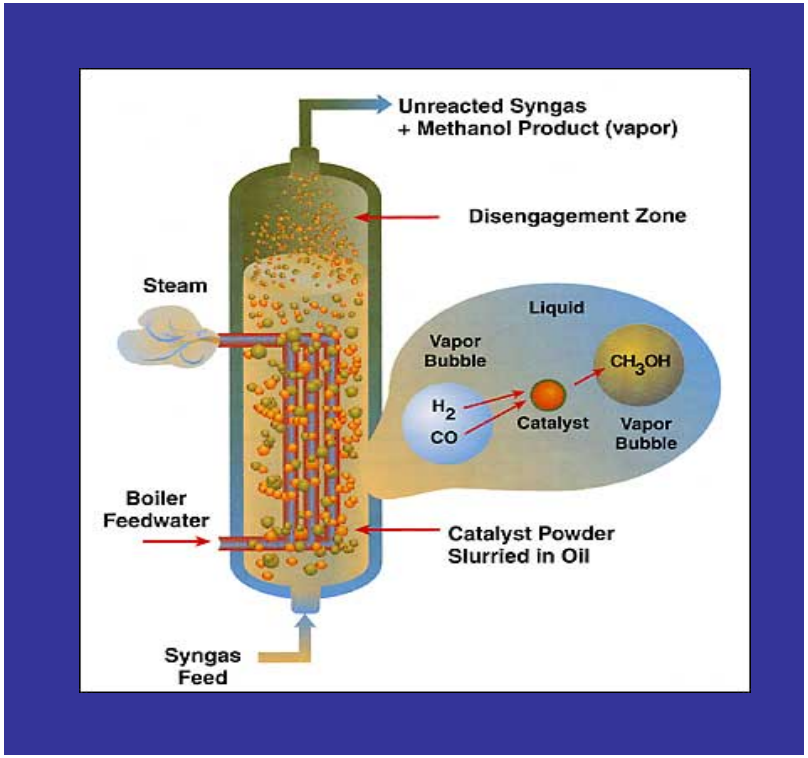
Minimal: Scarce minerals for some semiconductors (CdTe?)

Decarbonize Fuels



Coal to Synfuels with CCS*

***Carbon capture and storage**



Graphics courtesy of DOE Office of Fossil Energy

C originally in coal: assume half captured, half in synfuels

Effort needed for 1 slice

Annually produce synfuels from 3000 million tons coal, roughly current production; capture and store the CO_2 that would have been vented.

Potential Pitfalls:

The most carbon-intensive fuels become entrenched, because synfuel production proceeds, but CCS is thwarted.

Fossil Fuel-based CCS H_2*

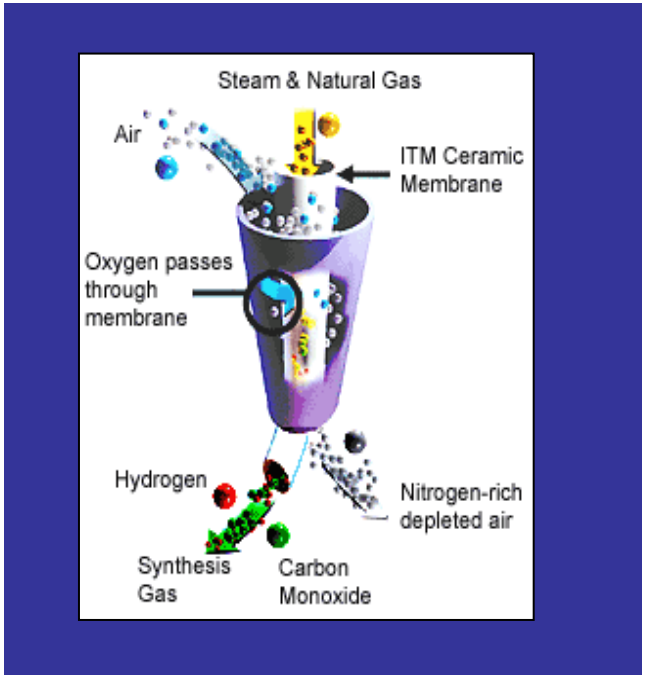
Carbon capture and storage

Effort needed for 1 slice:

For both coal and natural gas, roughly the same flows as for a slice of CCS electricity.

Today: ~40 Mt(H2)/yr produced from fossil fuels (almost all in refineries and for NH_3).

At these H_2 production sites ~0.1 GtC/yr vented as CO_2, often at high purity.



Potential Pitfalls:
Public acceptance of CO_2 storage
Global and local CO_2 leakage

H_2-infrastructure, H_2 safety

Graphics courtesy of DOE Office of Fossil Energy

Biofuels

Effort needed for 1 slice:

Annually, plant and sustain 4 million new hectares of high-yield (15 t/ha-yr) crops, back out gasoline and diesel

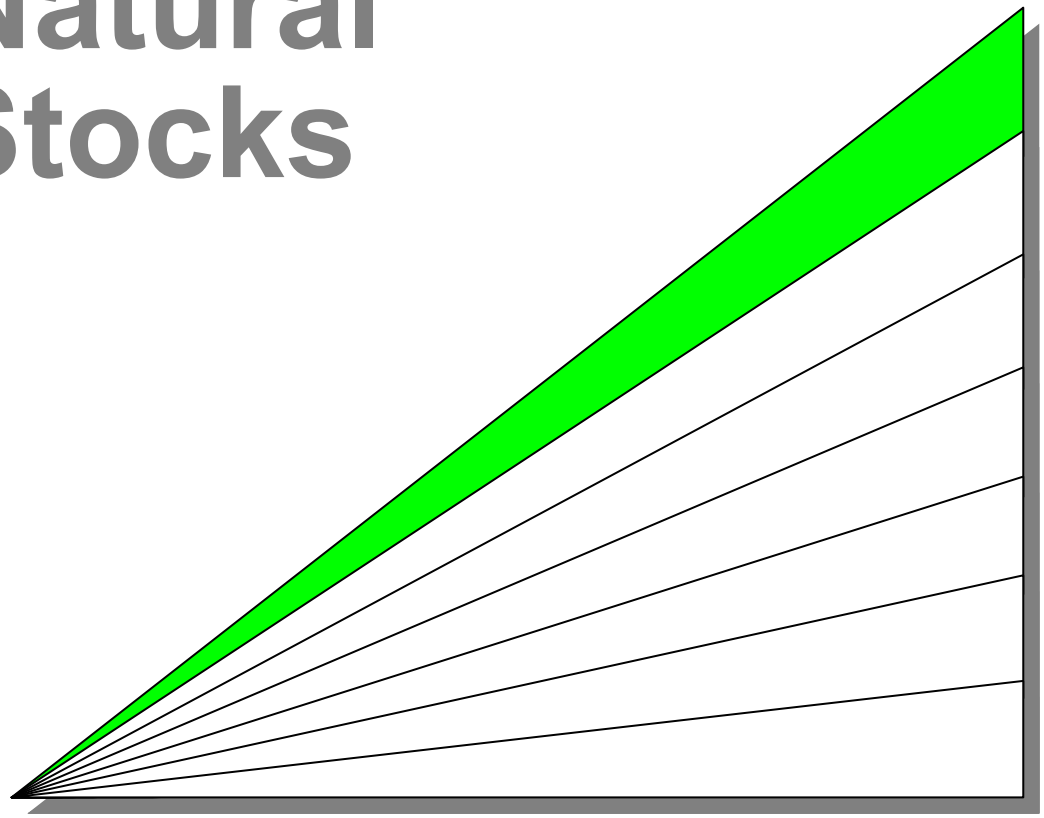
By 2050, have planted area equal to U.S. cropland (200 million hectares)

Photos courtesy of NREL

Potential Pitfalls:

Competing land use, biodiversity

Natural Stocks



Natural Stocks

Effort needed for 1 slice:

Reduce tropical deforestation by 100% instead of 50% by 2054, i.e. from ≈1.0 to 0.0 instead of to 0.5 GtC/y

AND

Rehabilitate 400 million hectares (Mha) temperate OR 300 Mha tropical forest

Photo courtesy of NREL, SUNY Stonybrook

Potential Pitfalls:

Reversibility, verification

Effort needed for 1 slice:

Conservation tillage on *all* cropland (1600 Mha) by 2054; already practiced on 110 Mha.

Summary: What's appealing about Wedges and Slices?

The stabilization wedge:

- Does not concede doubling is inevitable.
- Shortens the time frame to within business horizons.

Slices:

- Decomposes a heroic challenge (the wedge) into a limited set of monumental tasks
- Establishes a unit of action that permits quantitative discussion of cost, pace, risk.
- Establishes a unit of action that facilitates quantitative comparisons and trade-offs

The Argument of This Talk

1. Distinguish two responses to the global carbon problem:
   A. Act now in a big way
   B. Delay (learn now, act later)
2. Do we have the tools to act in a big way?
   If not, no reason to ask if we *should act*.
   Most of the talk is an argument that we *do* have the tools.
3. So, we can't dodge the question: *Should* we act now in a big way? And my answer is: Yes.

Acknowledgements

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