An Overview of CO_2 Capture Technology for Fossil Fuel Power Plants

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Outline of Talk

- Why the interest in CO_2 capture and storage (CCS)?
- What is the current status of CO_2 capture technology?
- What options are available for power plants?
- How effective are current capture systems?
- How does it affect other emissions?
- How much does it cost?
- What is the outlook for improved technology?
- What are the key needs to develop these technologies?

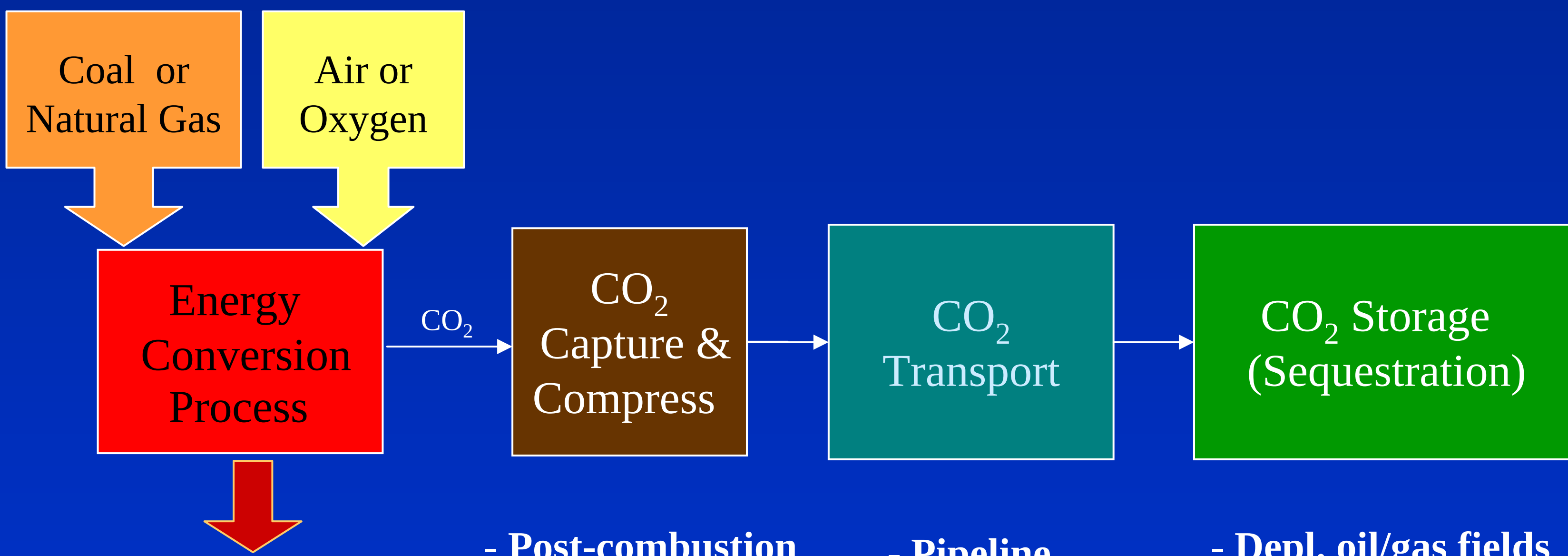
Why the Interest ?

- Coal and other fossil fuels will continue to be used extensively for many decades to come—no easy or fast alternatives on a large scale
- CO_2 capture and storage (CCS) offers a way to use fossil fuels (especially coal) with little or no CO_2 emissions—a potential bridging strategy
- Energy models indicate that including CCS in a portfolio of options significantly lowers the cost of achieving the deep long-term reductions needed to mitigate climate change

Can We Have Our Cake and Eat it Too?

Can We Have Our Coal Without CO_2?

Schematic of a CCS System



Useful Products

(Electricity, Fuels, Chemicals, Hydrogen)

- **Post-combustion**
- **Pre-combustion**
- Oxyfuel combustion

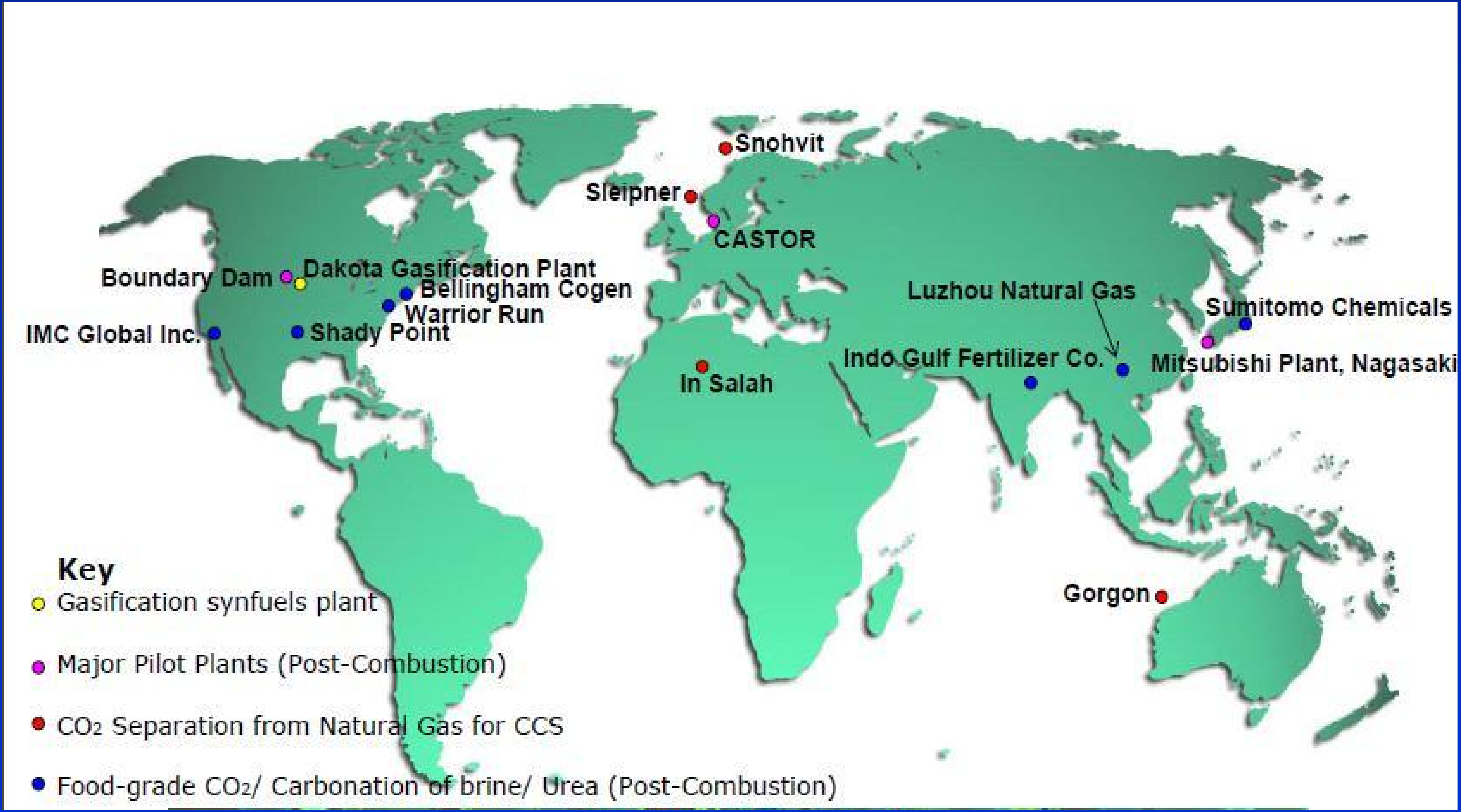
- **Pipeline**
- *Tanker*

- **Depl. oil/gas fields**
- **Deep saline reservoirs**
- *Unmineable coal seams*
- *Ocean*
- *Mineralization*

Status of Capture Technology

- CO_2 capture technologies are commercial and widely used in industrial processes, mainly in the petroleum and petrochemical industries (e.g., for ammonia production and processing of natural gas)
- CO_2 capture also has been applied to several gas-fired and coal-fired boilers (to produce commodity CO_2 for sale), but at scales that are small compared to a large modern power plant
- Integration of CO_2 capture, transport and geologic sequestration has been demonstrated in several industrial applications, but not yet at an electric power plant

Current CO_2 Capture Projects



Source: IEA GHG, 2007

What options are available?

Many Ways to Capture CO_2

- **CO2 Separation and Capture**
  - **Absorption**
    - Chemical
      - MEA
      - Caustic
      - Other
    - Physical
      - Selexol
      - Rectisol
      - Other
  - **Adsorption**
    - Adsorber Beds
      - Alumina
      - Zeolite
      - Activated C
    - Regeneration Method
      - Pressure Swing
      - Temperature Swing
      - Washing
  - **Cryogenics**
  - **Membranes**
    - Gas Separation
      - Polyphenyleneoxide
      - Polydimethylsiloxane
    - Gas Absorption
      - Polypropelene
    - Ceramic Based Systems
  - **Microbial/Algal Systems**

Choice of technology depends strongly on application

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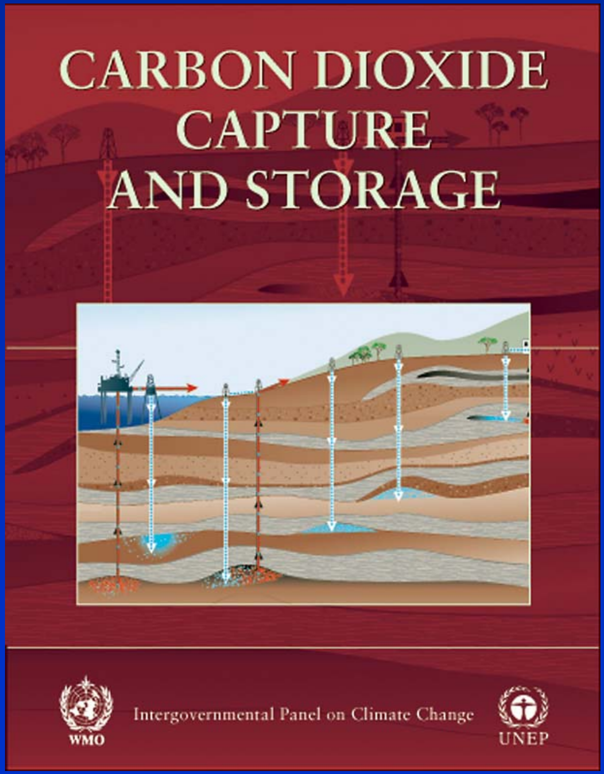
IPCC Special Report Examines CO_2 Capture Technology in Detail

The Intergovernmental Panel on Climate Change (IPCC) Web Site (www.ipcc.ch) has:

- Summary for Policymakers
- Technical Summary
- Full Technical Report

(also available from Cambridge University Press, 2005)

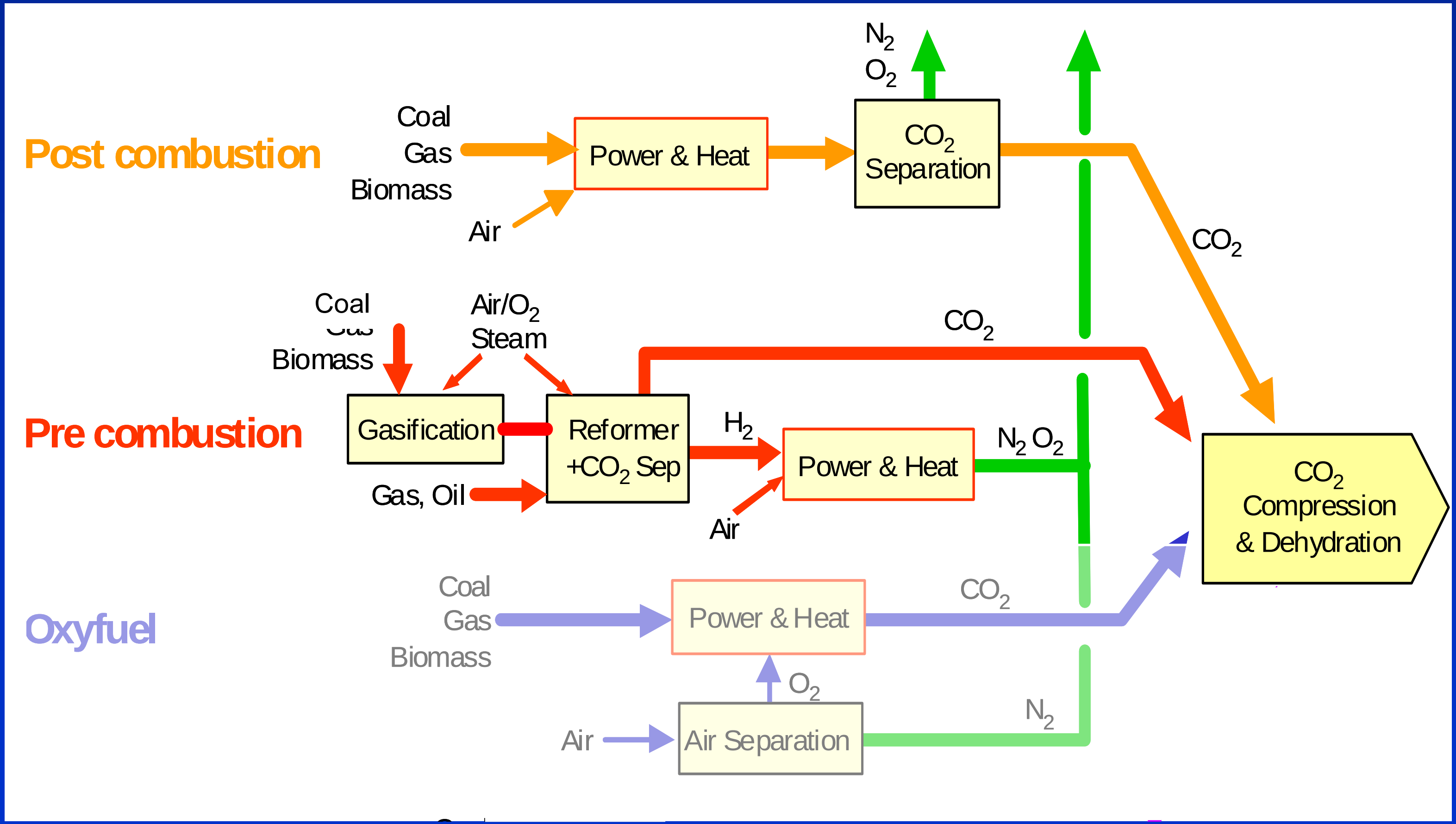


Leading Candidates for CCS

- Fossil fuel power plants
  - Integrated coal gasification combined cycle (IGCC)
  - Pulverized coal combustion (PC)
  - Natural gas combined cycle (NGCC)
- Other large industrial sources of CO_2 such as:
  - Refineries, fuel processing, and petrochemical plants
  - Hydrogen and ammonia production plants
  - Pulp and paper plants
  - Cement plants

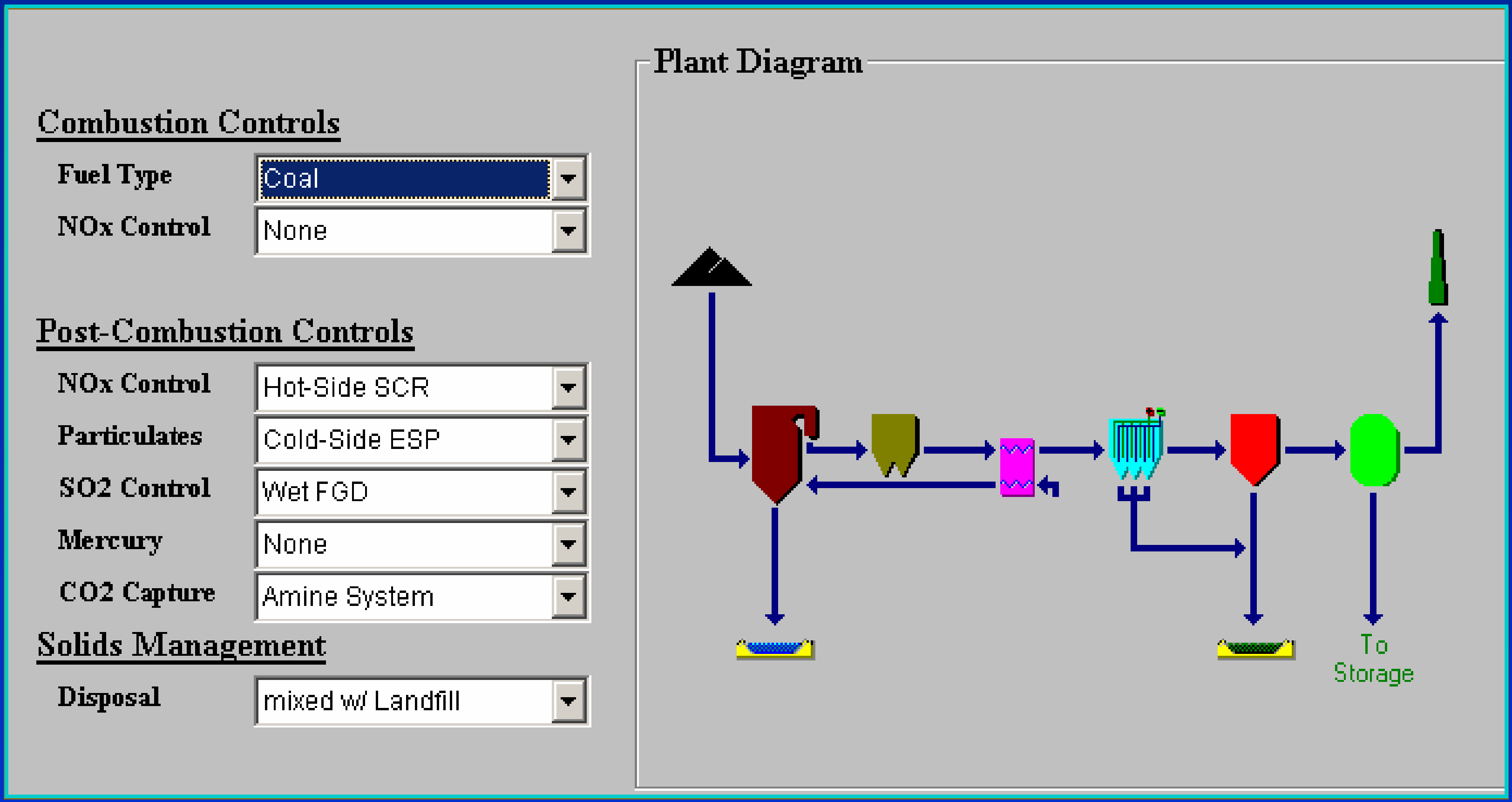
– Focus of this talk is on power plants –

CO_2 Capture Options for Power Plants

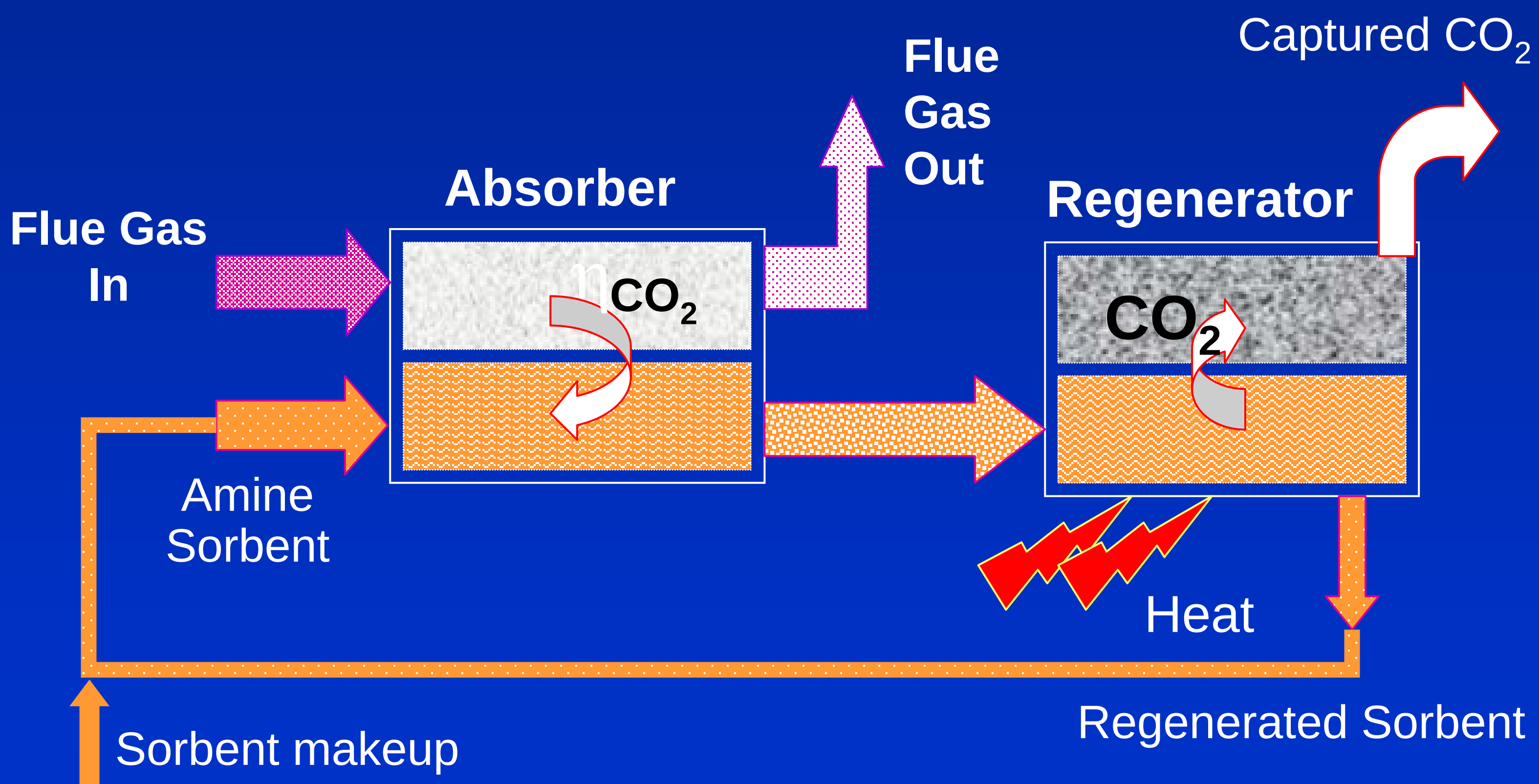


Source: IPCC SRCCS, 2005

Pulverized Coal-Fired Power Plant with Post-Combustion CO_2 Capture



Schematic of Amine Capture System



Typical CO_2 Removal Efficiency ≈ 90%

Examples of Post-Combustion CO_2 Capture at Coal-Fired Plants

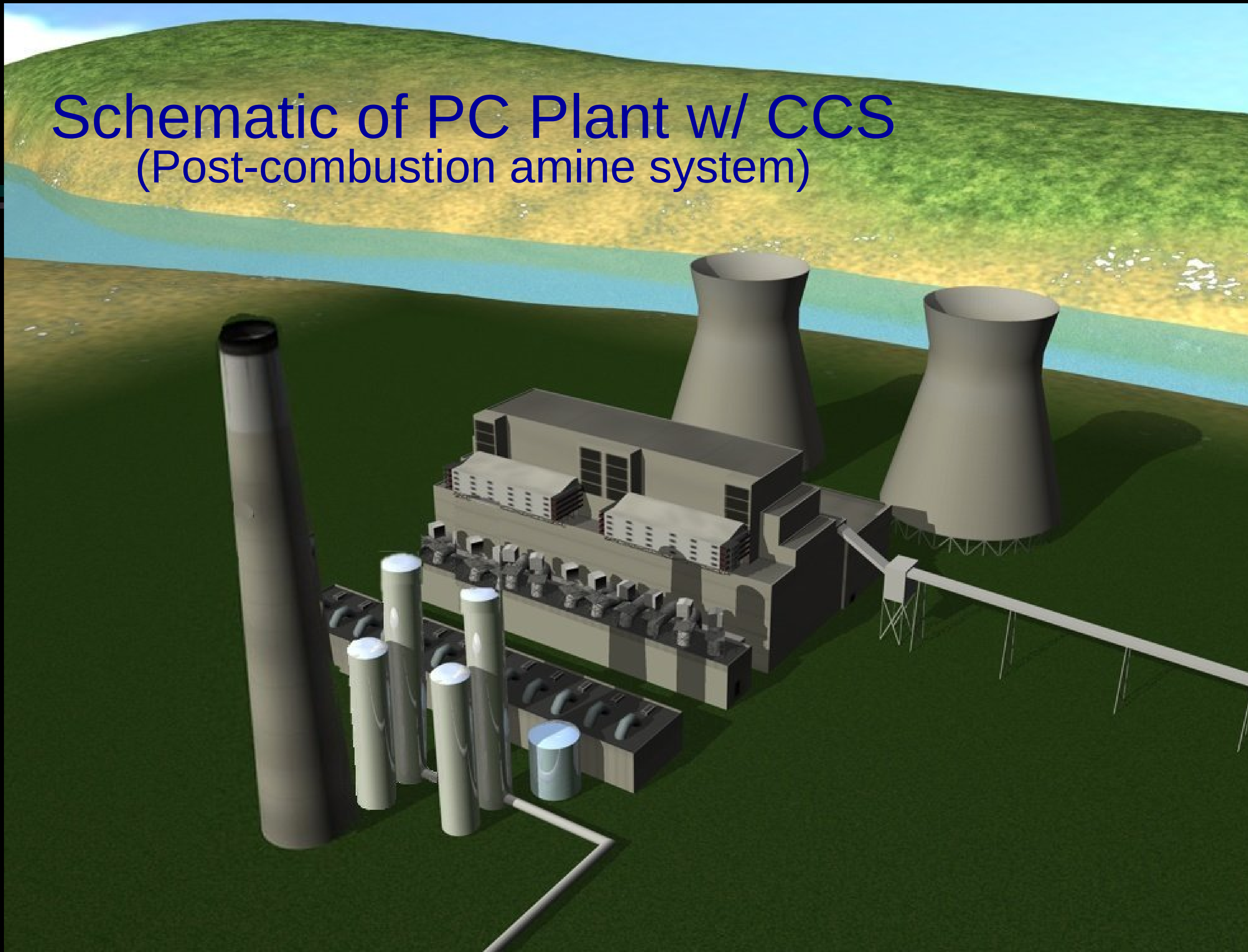
(Source: ABB Lummus)

Shady Point Power Plant
(Panama, Oklahoma, USA)

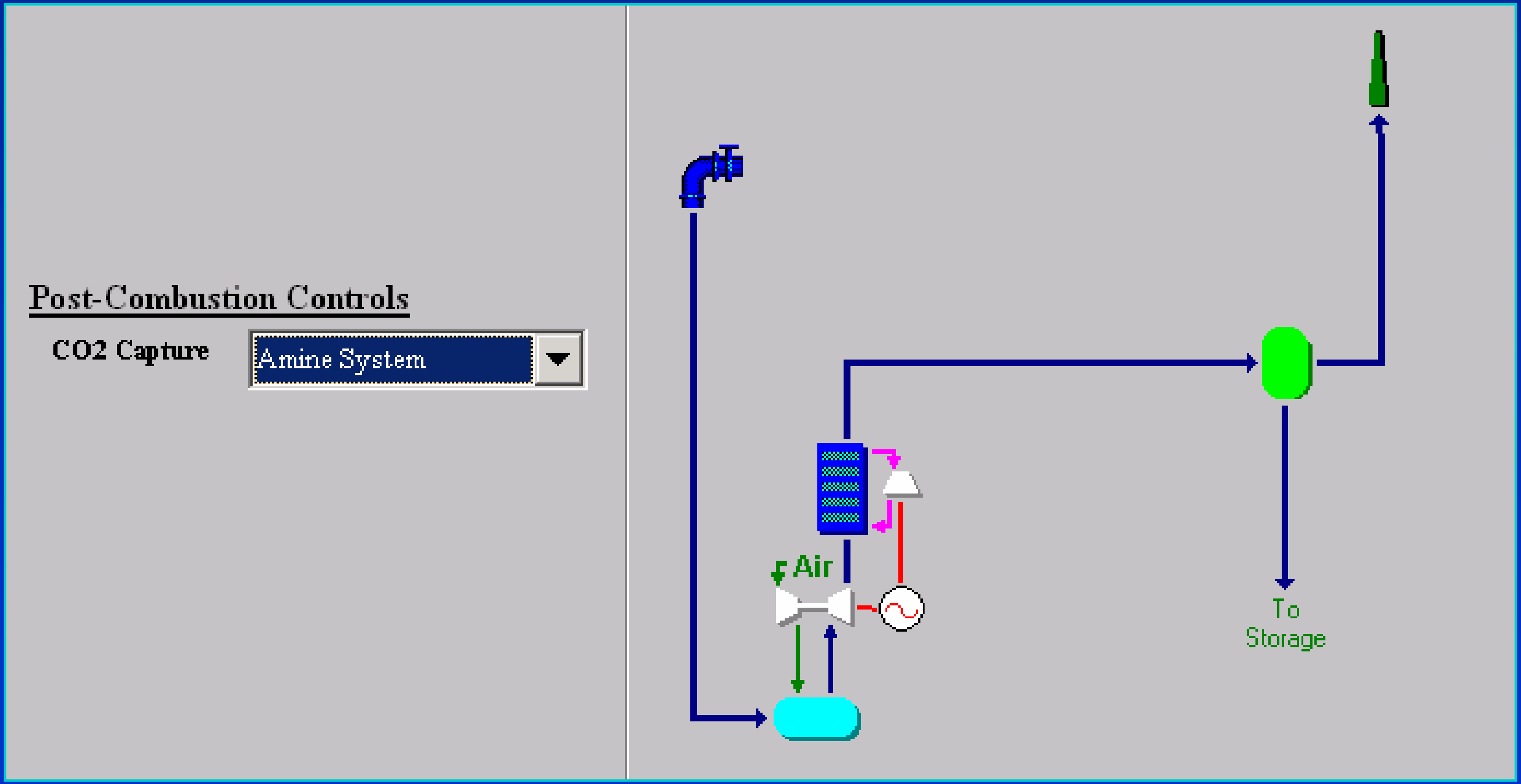
(Source: (IEA GHG)

Warrior Run Power Plant
(Cumberland, Maryland, USA)

Schematic of PC Plant w/ CCS
(Post-combustion amine system)

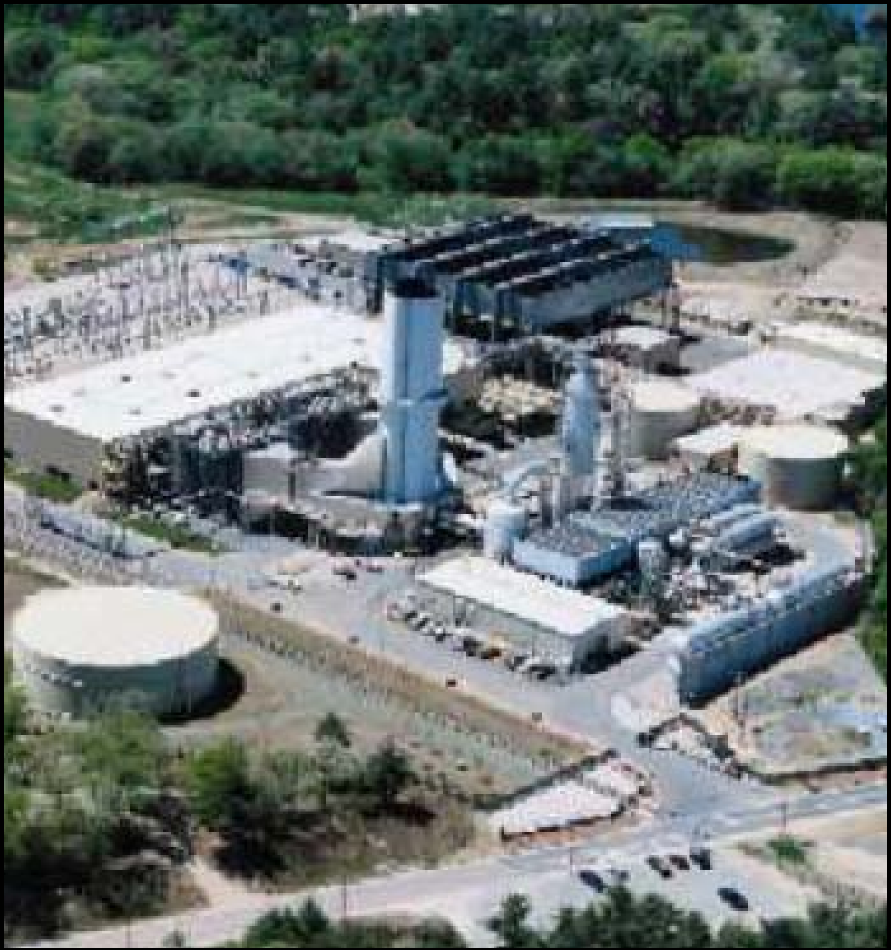


Natural Gas Combined Cycle Plant with Post-Combustion CO_2 Capture



Examples of Post-Combustion CO_2 Capture at Gas-Fired Plants

(Source: Suez Energy Generation))



Bellingham Cogeneration Plant

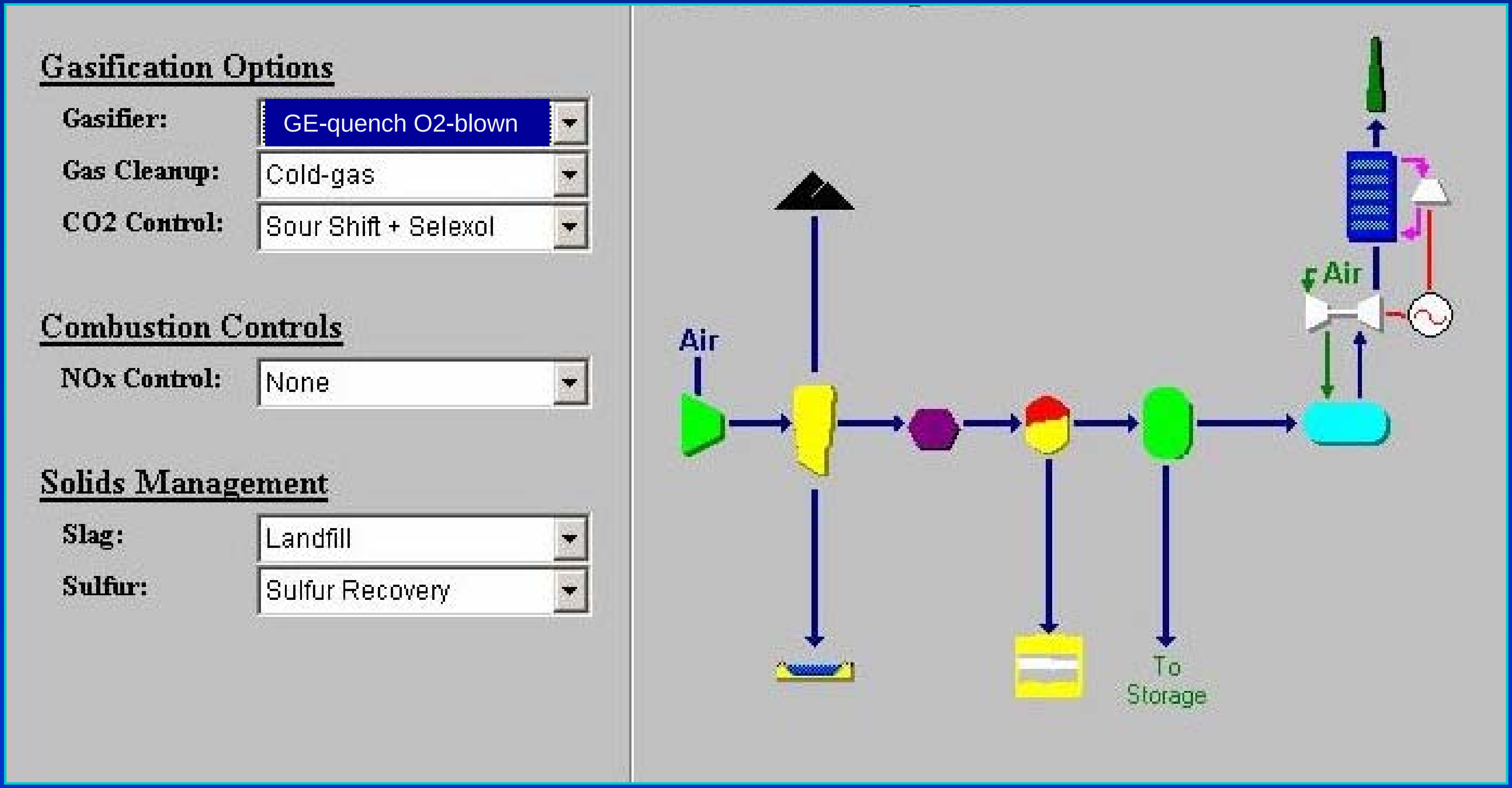
(Bellingham, Massachusetts, USA)

(Source: Mitsubishi Heavy Industries)

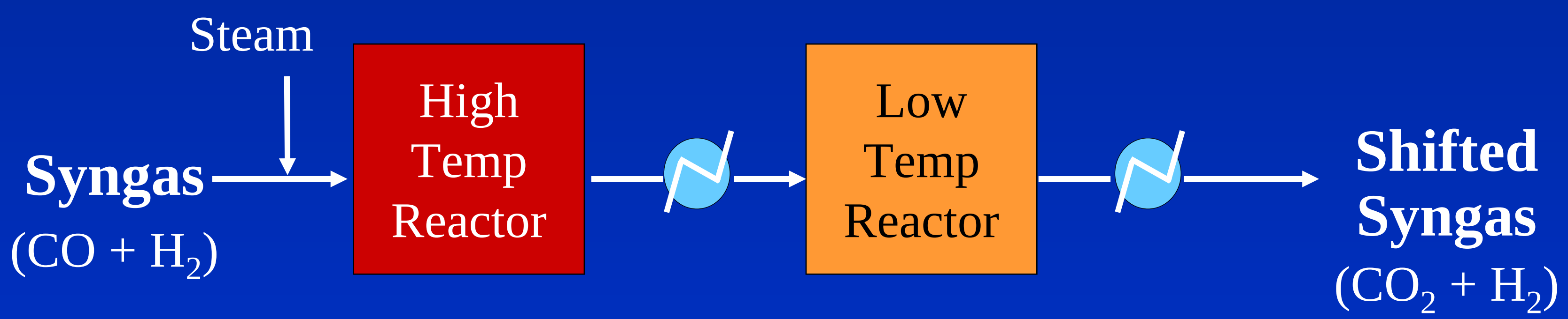
Petronas Urea Plant Flue Gas

(Keda, Malaysia)

Integrated Coal Gasification Combined Cycle Plant w/ Pre-Combustion Capture

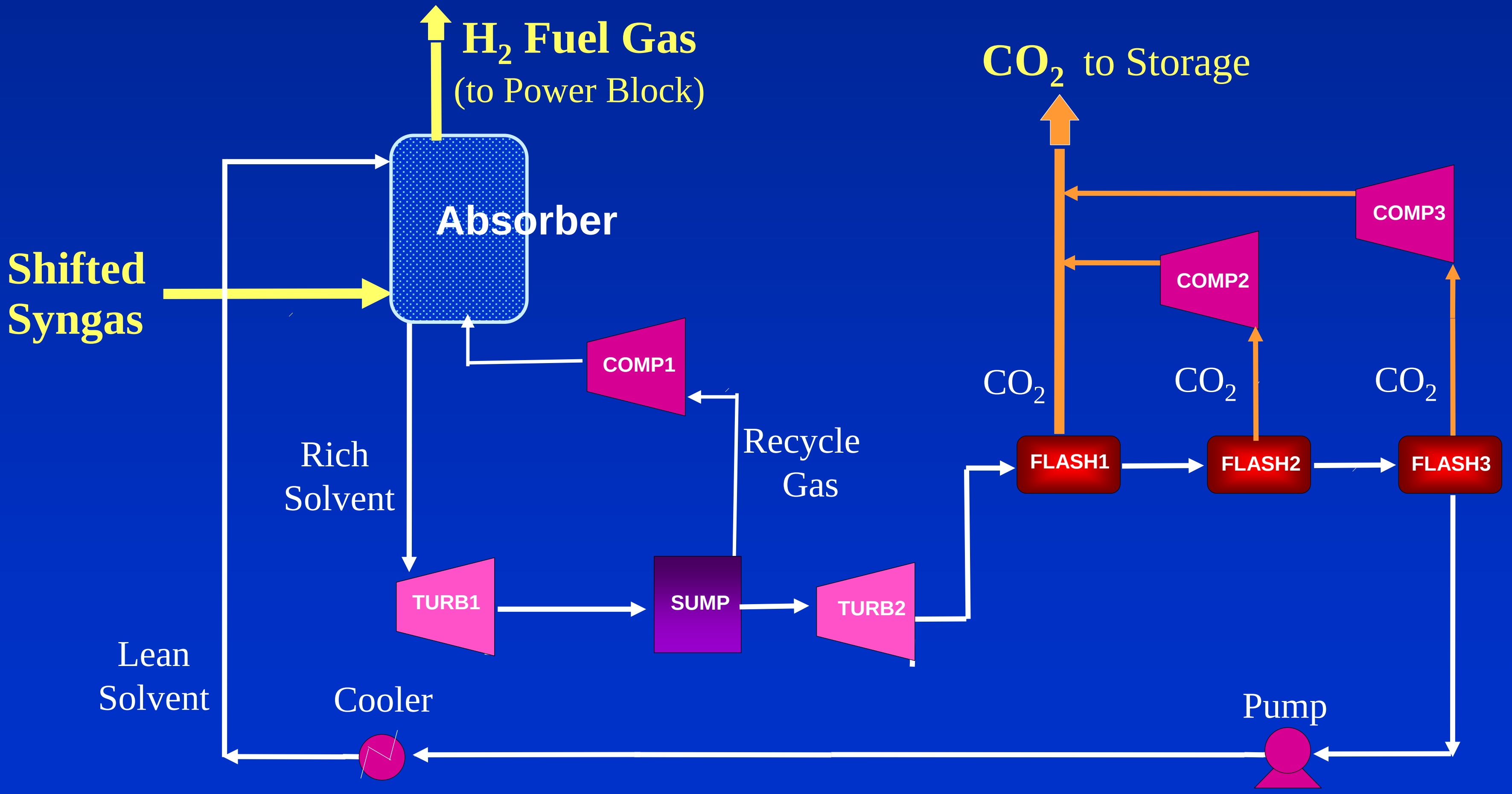


Water-Gas Shift Reactor Schematic



$$CO + H_2O \rightarrow CO_2 + H_2$$

Selexol CO_2 Capture Schematic



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Examples of Pre-Combustion CO_2 Capture Systems

(Source: Chevron-Texaco)

Petcoke Gasification to Produce H_2

(Coffeyville, Kansas, USA)

(Source: Dakota Gasification)

Coal Gasification to Produce SNG

(Beulah, North Dakota, USA)

Integrated Coal Gasification Combined Cycle (IGCC) Plant

Polk Power Station, Tampa, Florida

(250 MW, no CO_2 capture)

Source: TECO, 2004

Schematic of IGCC w/ CO_2 Capture

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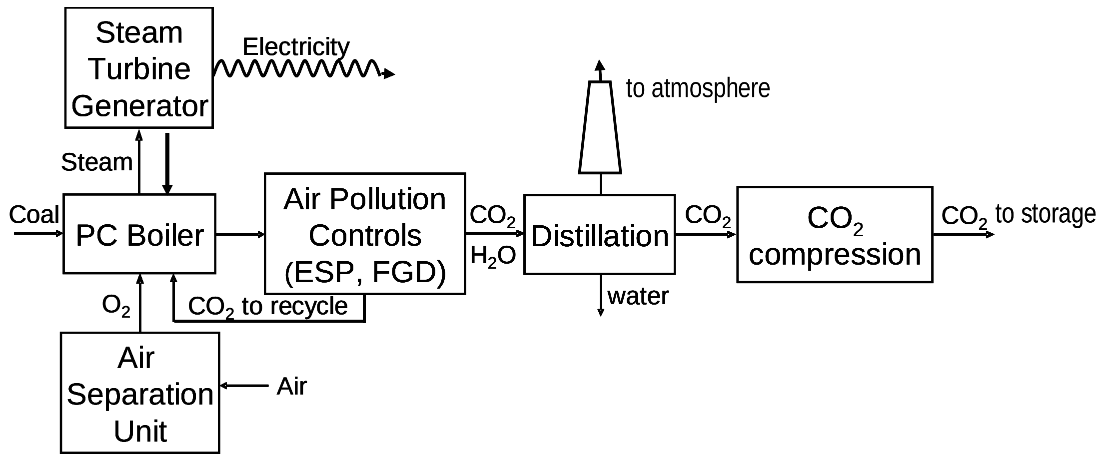
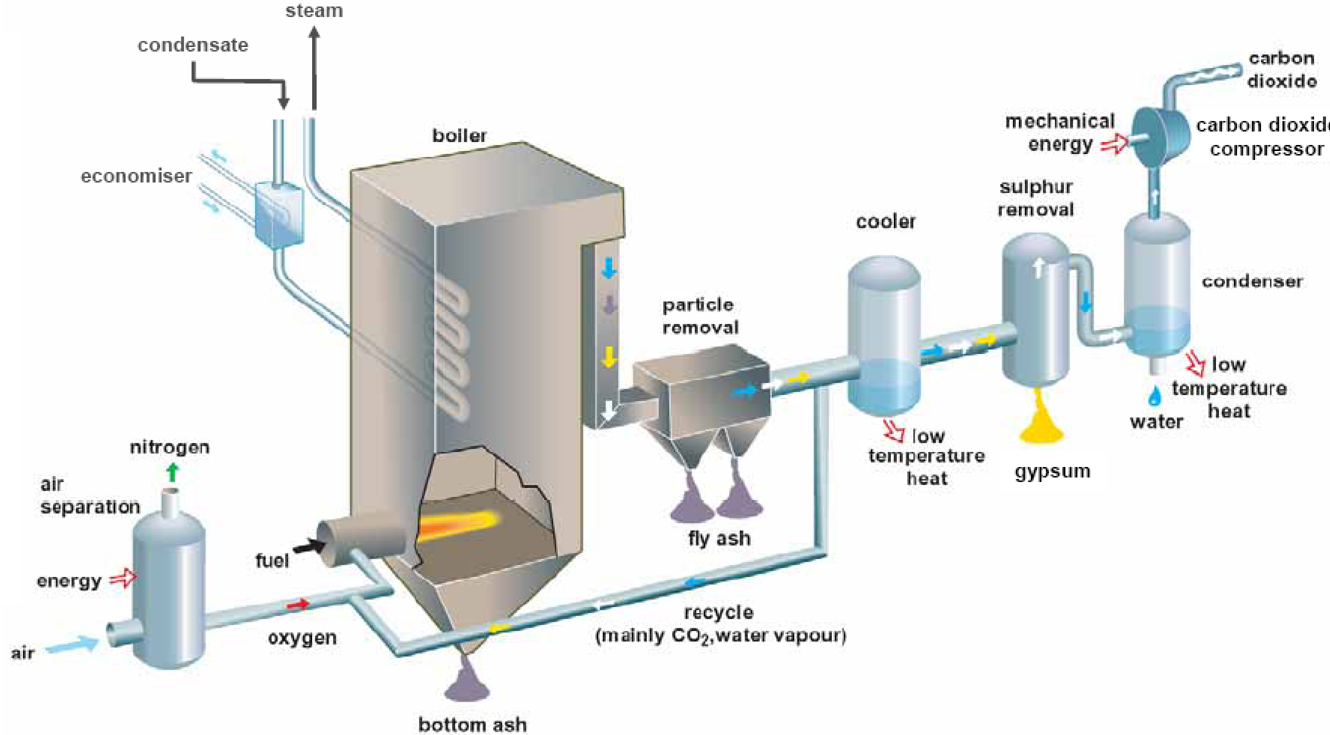
Pulverized Coal-Fired Power Plant with Oxyfuel Combustion Capture



The Vattenfall 30 MW_{th} Oxy-Coal Pilot Boiler with CO_2 capture at Schwarze Pumpe (Germany), starting mid-2008



Source: Vattenfall, 2006

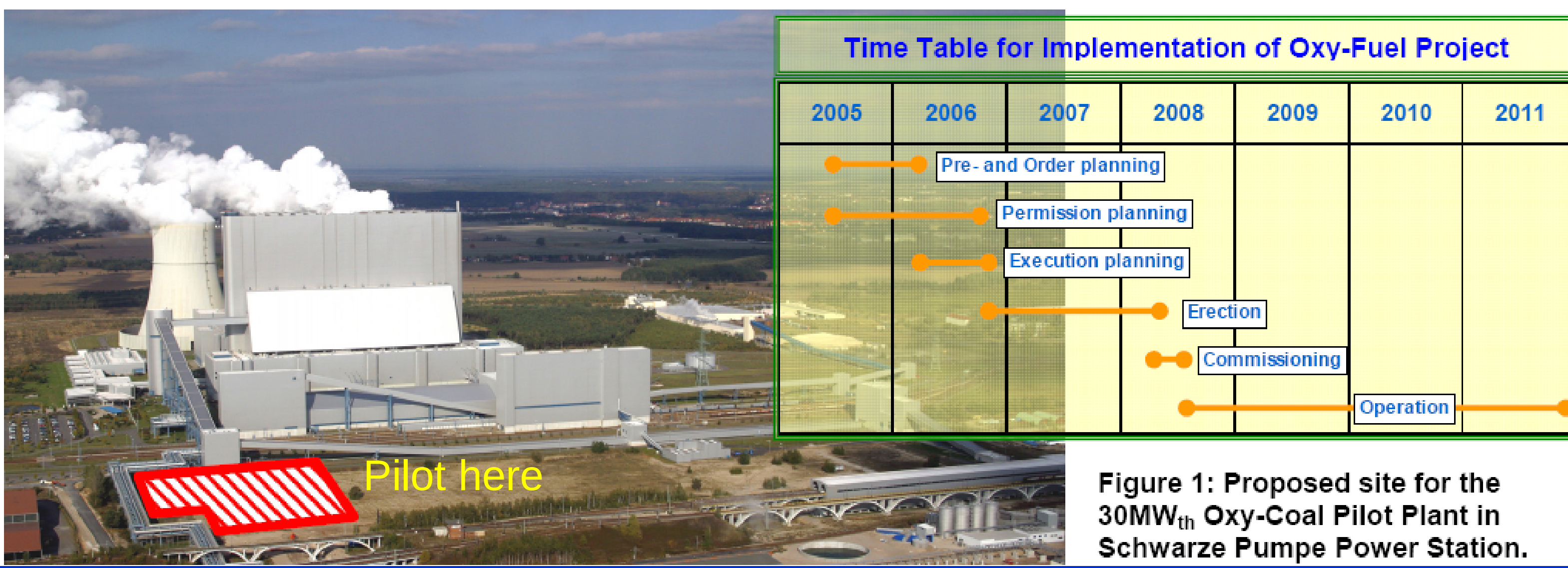


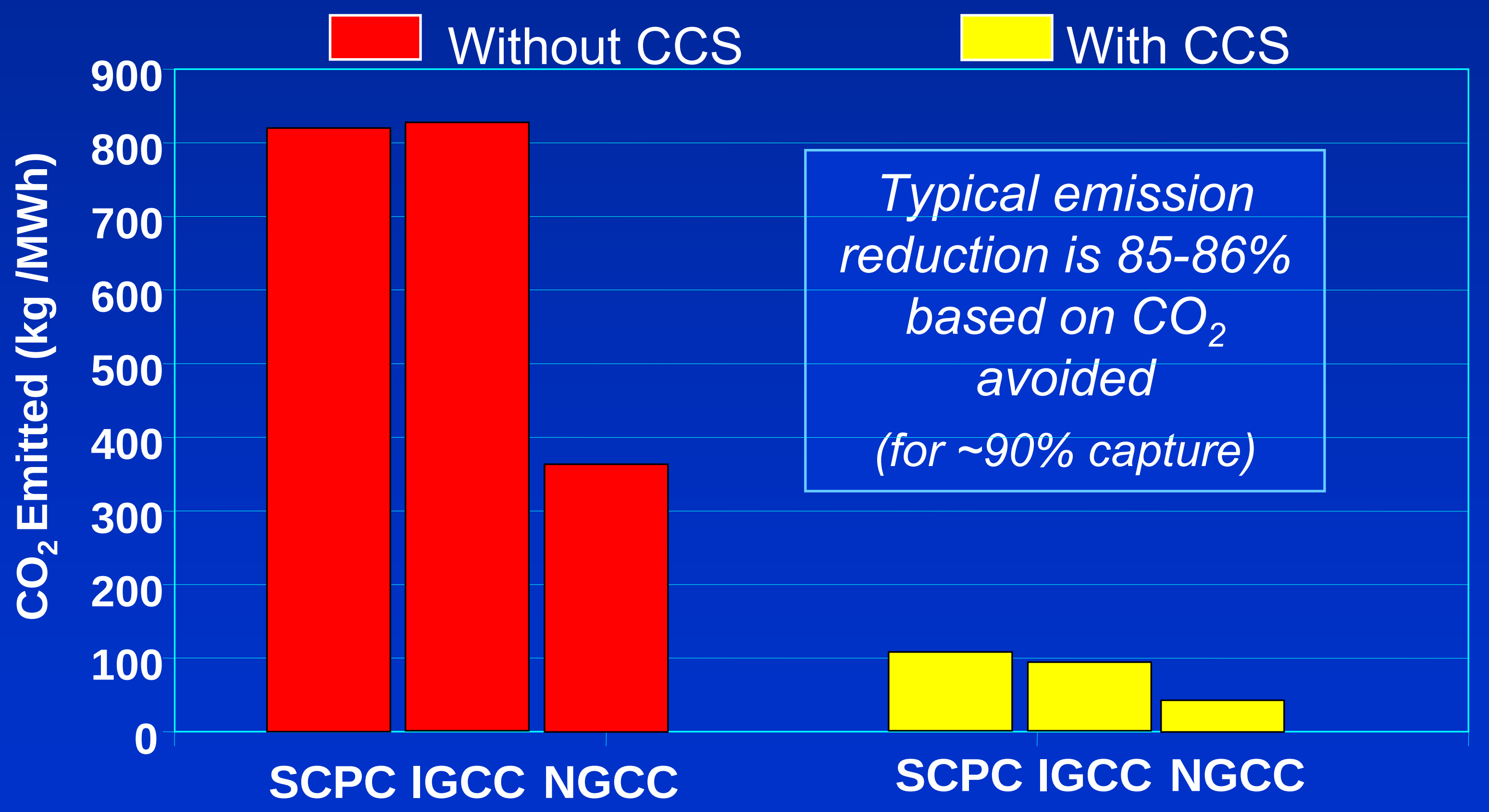
Figure 1: Proposed site for the 30MW_{th} Oxy-Coal Pilot Plant in Schwarze Pumpe Power Station.

Summary of Capture Status

- Several existing applications of CO_2 capture at scales small compared to a modern power plant, but
- Several new large-scale projects proposed in different countries to demonstrate pre-combustion, post-combustion and oxyfuel fuel combustion over the coming decade using a variety of fuels (coal, gas, liquids) in power plant and related industrial applications

How effective are current CO_2 capture systems?

Illustrative CO_2 Emission Rates for New Power Plants (kg CO_2/MWh)



Is There an Optimal Capture Efficiency?

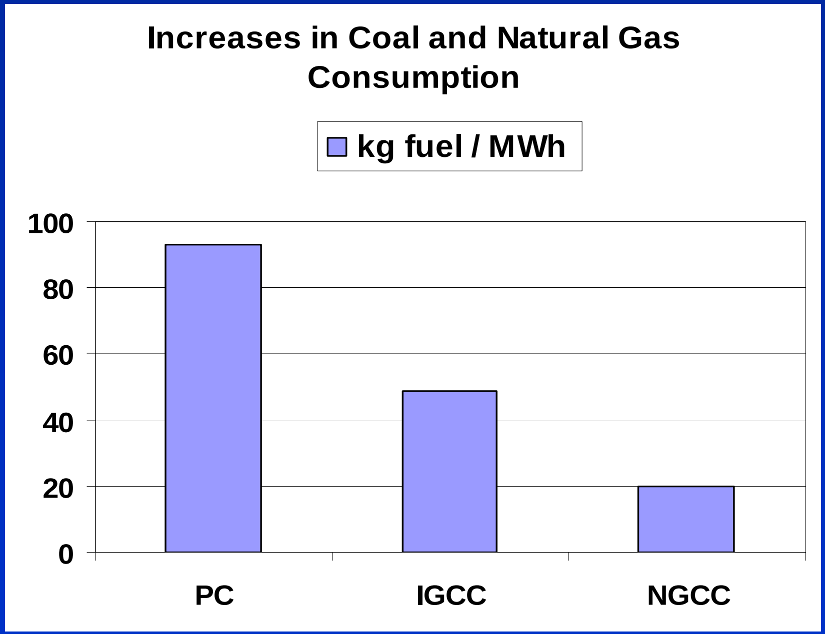
- Our studies show that the most cost-effective level of CO_2 capture (minimum cost per ton of CO_2 avoided) occurs at removal efficiencies of about 85%–90% for both PC and IGCC plants using current technology
- Optimal level varies slightly with plant size and other factors that affect the number of absorber and compressor trains required for CO_2 capture and compression

What is the impact on other plant emissions ?

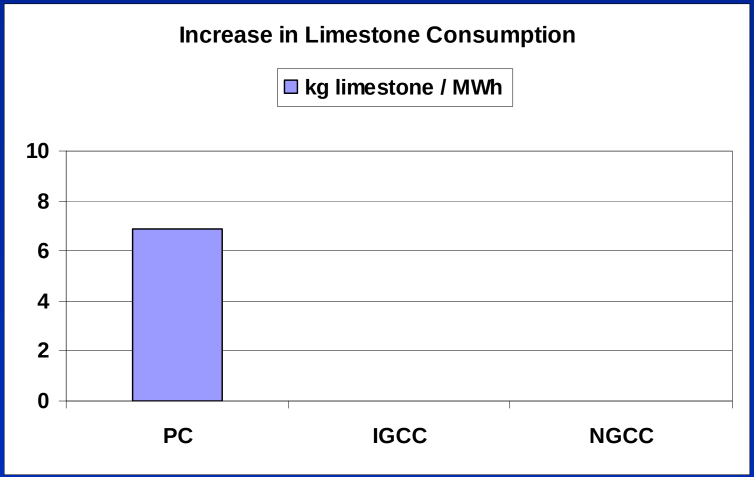
Importance of the CCS "Energy Penalty"

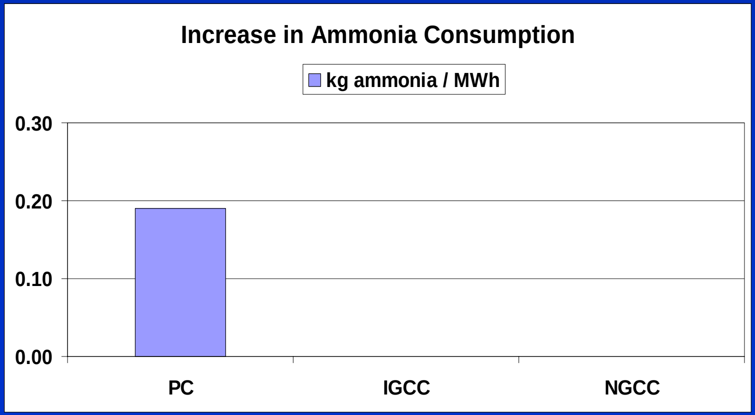
- CCS energy requirements are defined here as the *increase in fuel energy input per unit of net electrical output* (relative to a similar plant without capture)
- This directly affects the plant-level resource requirements and emissions per MWh of:
  - Fuel and reagent use
  - Air pollutant emissions
  - Solid and liquid wastes
  - Upstream (life cycle) impacts
- Additional energy/MWh for representative plants:
  - PC = 31%; IGCC = 16%; NGCC = 17%

Case Study Increases in Fuel and Reagent Consumption

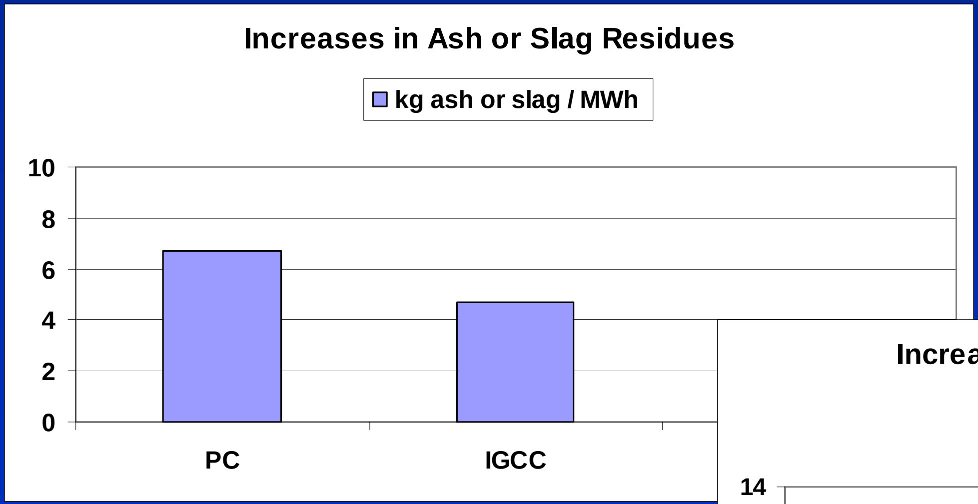


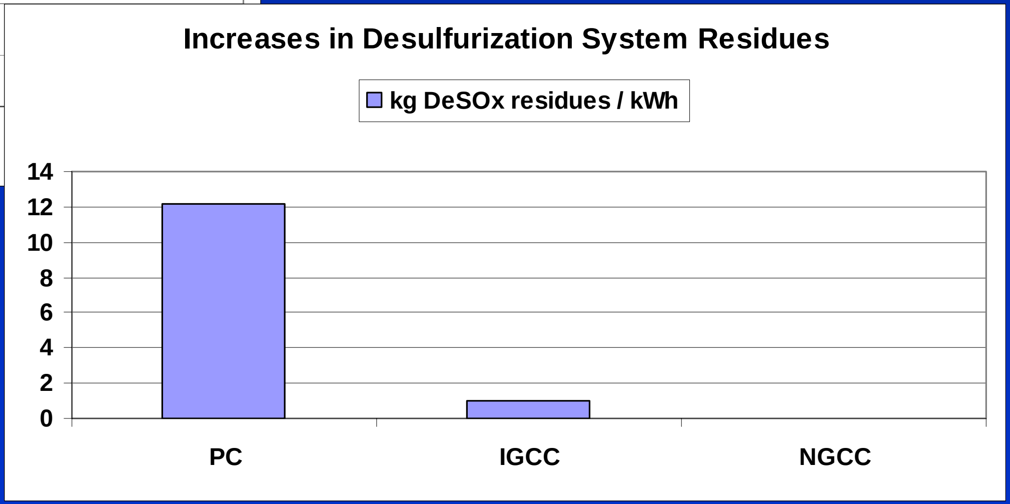
Source: Rubin, et.al, 2005





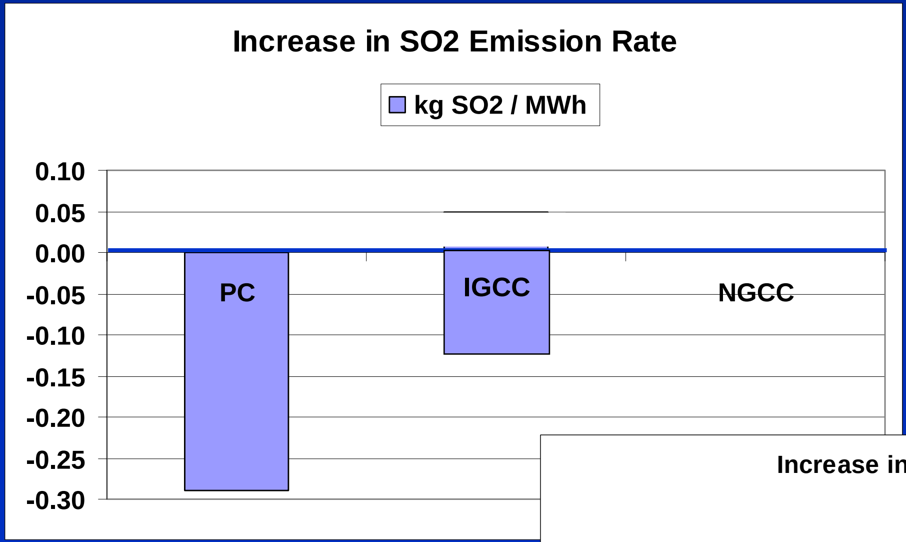
Case Study Increases in Solid Wastes & Plant Byproducts

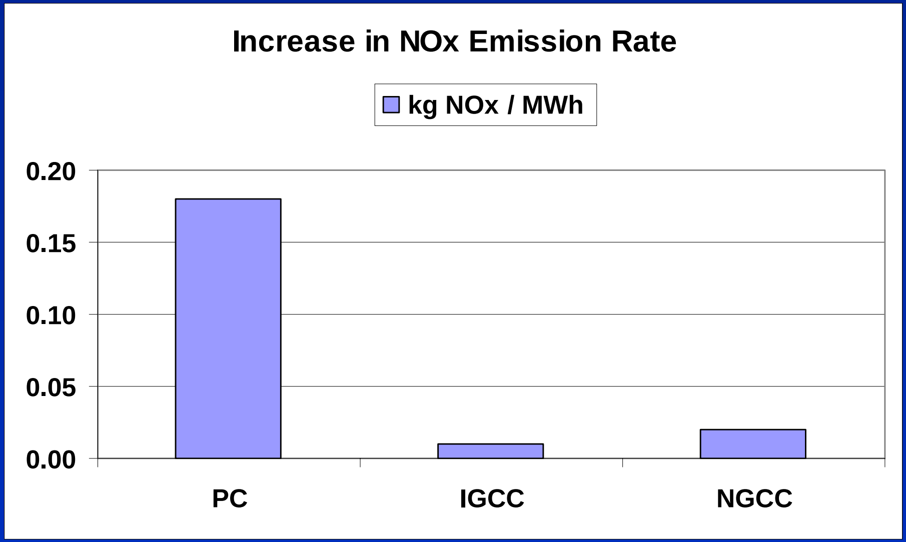


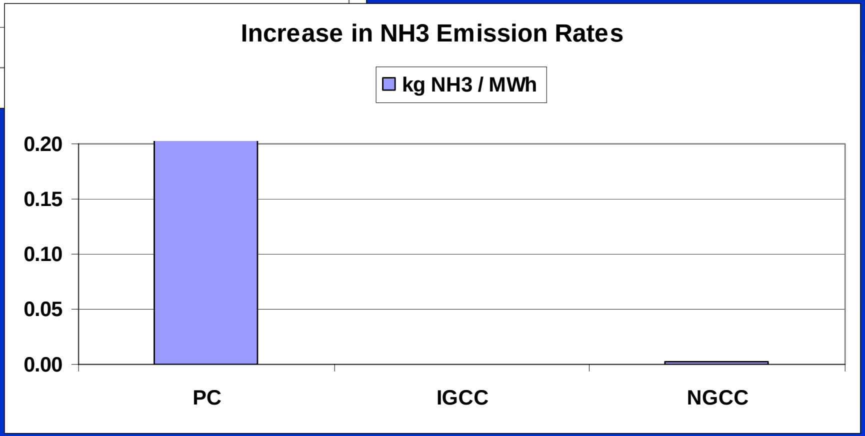


Source: Rubin, et.al, 2005

Case Study Increases in Air Emission Rates







Source: Rubin, et.al, 2005

Case Study Impacts of CCS on Plant Resource Use and Emission Rates

(Capture plant rate and increase over reference plant rate, kg/MWh)

Capture Plant Parameter	PC		IGCC		NGCC	
	Rate	Increase	Rate	Increase	Rate	Increase
Resource Consumption	**(All values in kg/MWh)**					
Fuel	390	93	364	50	156	23
Limestone	27.5	6.8	-	-	-	-
Ammonia	0.80	0.19	-	-	-	-
CCS Reagents	2.76	2.76	0.005	0.005	0.80	0.80
Solid Wastes/ Byproduct						
Ash/slag	28.1	6.7	34.2	4.7	-	-
FGD residues	49.6	12.2	-	-	-	-
Sulfur	-	-	7.7	1.2	-	-
Spent CCS sorbent	4.05	4.05	0.005	0.005	0.94	0.94
Atmospheric Emissions						
CO_2	107	*–704*	97	*–720*	43	*–342*
SO_x	0.001	*– 0.29*	0.011	*–0.13*	-	-
NO_x	0.77	0.18	0.10	0.01	0.11	0.02
NH_3	0.23	0.22	-	-	0.002	0.002

Reducing Environmental Impacts

- New or improved power generation and CO_2 capture technologies promise to reduce CCS impacts by:
  - Improving overall plant efficiency
  - Reducing CCS energy requirements
  - Increasing CO_2 capture efficiency
  - Maximizing pollutant co-capture & disposal

More on this a little later

How much does CCS cost?

Many Factors Affect Reported Costs of CO_2 Capture & Storage

- Choice of CCS Technology
- Process Design and Operating Variables
- Economic and Financial Parameters
- Choice of System Boundaries; *e.g.,*
  - One facility vs. multi-plant system (regional, national, global)
  - GHG gases considered (CO_2 only vs. all GHGs)
  - Power plant only vs. partial or complete life cycle
- Time Frame of Interest
  - Current technology vs. future (improved) systems
  - Consideration of technological "learning"

Different Measures of Cost

- Cost of Electricity (\$/MWh)

$$= \frac{(TCC)(FCF) + FOM}{(CF)(8760)(MW)} + VOM + (HR)(FC)$$

- Cost of CO_2 Avoided (\$/ton CO_2 avoided)

$$= \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(CO_2/MWh)_{ref} - (CO_2/MWh)_{ccs}}$$

- Cost of CO_2 Abated (\$/ton CO_2 reduced)

$$= \frac{(\$\ NPV)_{ccs} - (\$\ NPV)_{reference}}{(CO_2)_{ref} - (CO_2)_{ccs}}$$

Ten Ways to Reduce the Estimated Cost of CO_2 Abatement

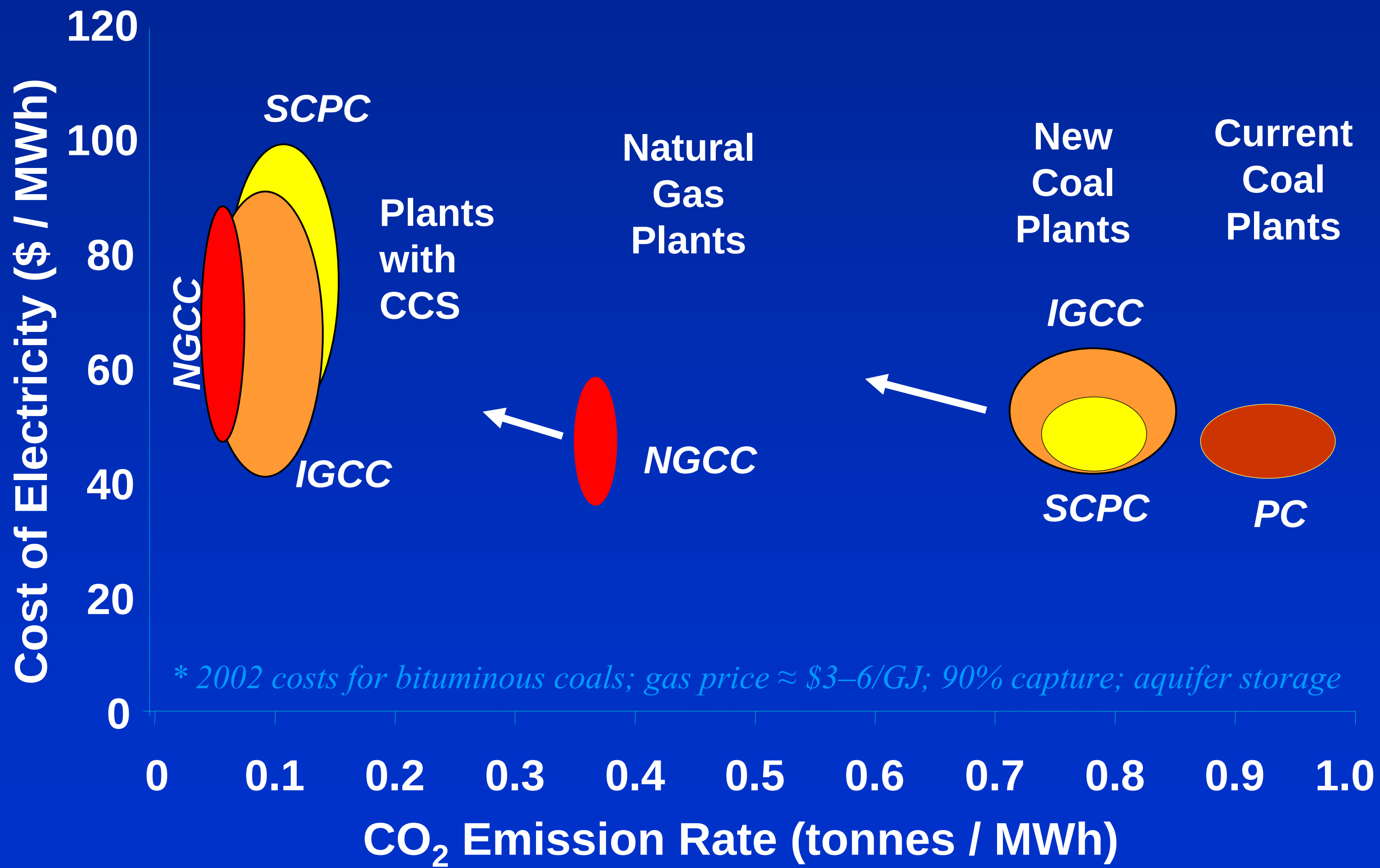
10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel costs
7. Assume EOR credits for CO_2 storage
6. Omit certain capital costs
5. Report \$/ton CO_2 based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high plant utilization (capacity factor)
1. Assume **all of the above !**

. . . *and we have not yet considered the CCS technology!*

Important Reminders

- No one has yet built and operated a CO_2 capture and sequestration system at a large-scale (e.g., 500 MW) power plant
- Hence, all the costs we're about to see are projections based on other applications; the "true" costs are not yet known
- In the last few years plant construction costs have escalated considerably (~30% from 2002 to 2006); current (2007) costs are thus higher than those reported in recent studies

Estimated Cost and Emissions of Power Plants with and without CCS*



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Representative CCS Costs for New Power Plants Using Current Technology

Incremental Cost of CCS Relative to Similar Plant without CCS	Natural Gas Combined Cycle Plant	Supercritical Pulverized Coal Plant	Integrated Gasification Combined Cycle Plant
Increase in plant capital cost for capture & compression	*~76%*	*~63%*	*~37%*
Increase in levelized COE (capture & compression only)	*~46%*	*~57%*	*~33%*
Added cost of CCS with aquifer storage ($/MWh)	**10–30**	**20–50**	**10–30**
Added cost of CCS with EOR storage ($/MWh)	**10–20**	**10–30**	**0–10**

Source: IPCC, 2005

Variability is due mainly to differences in site-specific factors. Added cost to consumers will depend on extent of CCS plants in the overall power generation mix over time

Cost of CO_2 Avoided ($/t$CO_2$)
(Based on Current Technology)

Levelized cost in 2002 US$ per tonne CO_2 avoided

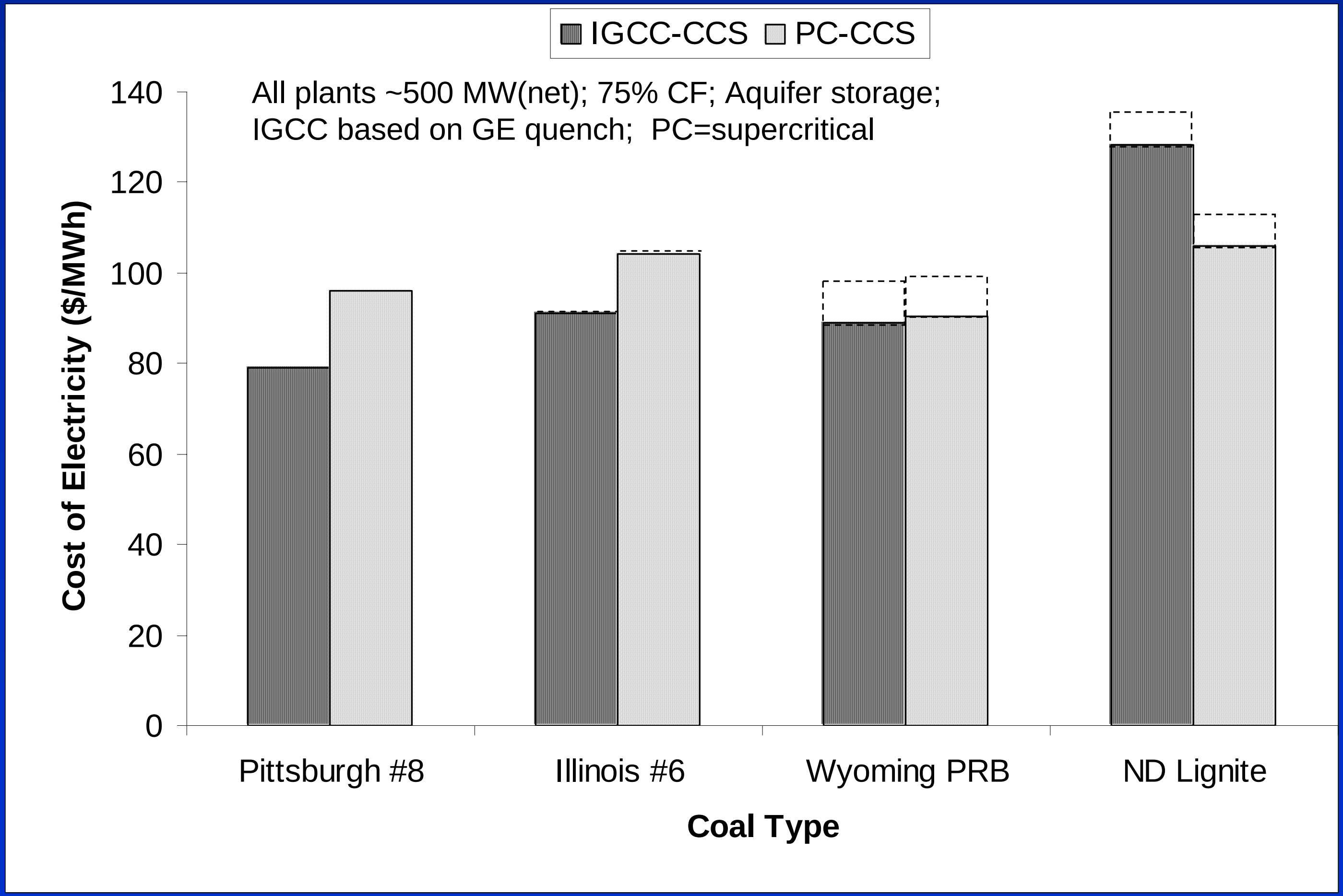
Cost of CO_2 Avoided Relative to Similar Plant without CCS	Natural Gas Combined Cycle Plant	Supercritical Pulverized Coal Plant	Integrated Gasification Combined Cycle Plant
Capture & compress only	35–75	30–50	15–35
+ Saline aquifer storage	40–90	30–70	15–55
+ EOR storage (credits)	20–70	10–45	(-5)–30

Source: IPCC, 2005

Different mixes of plants with and without CCS will have other avoidance costs; site-specific context is very important

Effects of Coal Quality on Cost of Electricity for PC and IGCC w/CCS

(2005 $/MWh; dashed lines based on constant $/GJ for all coals)



Detailed results and breakdown of costs for different systems are available in published papers and reports

Plant Type & Technology	Total Plant Costs ($2002)					
	Capital Cost		Total O&M Cost[5]		Total COE[6,7]	
	$/kW	% Total	$/MWh	% Total	$/MWh	% Total
NGCC Plant[1]	**916**	**100**	**38.5**	**100**	**59.1**	**100**
GTCC (power block)	660	72	2.2	6	17.1	29
CO_2 capture (amine system)	218	24	2.4	6	7.3	12
CO_2 compression	38	4	0.2	0	1.0	2
Fuel cost	0	0	33.6	87	33.6	57
PC Plant[2]	**1,962**	**100**	**29.3**	**100**	**73.4**	**100**
PC Boiler/turbine-generator area	1,282	65	5.7	19	34.5	47
AP controls (SCR, ESP, FGD)	241	12	4.1	14	9.5	13
CO_2 capture (amine system)	353	18	7.2	25	15.2	21
CO_2 compression	86	4	0.4	1	2.3	3
Fuel cost	0	0	11.9	41	11.9	16
IGCC Plant[3]	**1,831**	**100**	**21.3**	**100**	**62.6**	**100**
Air separation unit	323	18	1.7	8	8.9	14
Gasifier area	494	27	3.7	17	14.8	24
Sulfur removal/recovery	110	6	0.6	3	3.1	5
CO_2 capture (WGS/Selexol)	246	13	1.6	7	7.1	11
CO_2 compression	42	2	0.3	1	1.2	2
GTCC (power block)	616	34	2.0	9	15.8	25
Fuel cost	0	0	11.6	54	11.6	19
Oxyfuel Plant[4]	**2,417**	**100**	**24.4**	**100**	**78.9**	**100**
Air separation unit	779	32	3.1	13	20.6	26
PC boiler/turbine generator area	1,280	53	5.6	23	34.4	44
AP controls (ESP, FGD)	132	5	2.7	11	5.7	7
CO_2 distillation	160	7	1.4	6	5.0	6
CO_2 compression	66	3	0.5	2	1.9	2
Fuel cost	0	0	11.2	46	11.2	14

Notes: 1. NGCC plant = 432 MW (net); 517 MW (gross); two 7FA gas turbines; gas price = 4.0 $/GJ; 2. PC plant = 500 MW (net); 719 MW (gross); supercritical boiler; Pittsburgh #8 coal; price = 1.0 $/GJ; 3. IGCC plant = 490 MW (net); 594 MW (gross); 3 GE gasifiers + two 7FA gas turbines; Pgh #8 coal; price = 1.0 $/GJ; 4. Oxyfuel plant = 500 MW (net); 709 MW (gross); supercritical boiler; Pittsburgh #8 coal; price = 1.0 $/GJ; 5. Based on levelized capacity factor of 75% for all plants.; 6. COE is the levelized cost of electricity ; 7. Based on fixed charge factor of 0.148 for all plants; 8. The cost of reference plants with similar net output and no CO2 capture are: NGCC = $563/kW, $43.3/MWh; PC= $1229/kW, $44.9/MWh; IGCC = $1327/kW, $46.8/MWh.

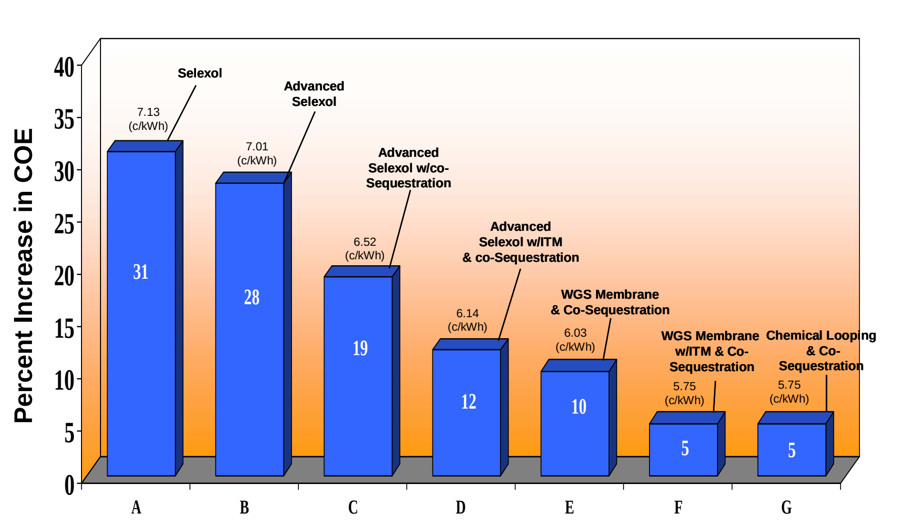
What is the outlook for improved capture technology?

Two Approaches to Estimating Future Technology Costs

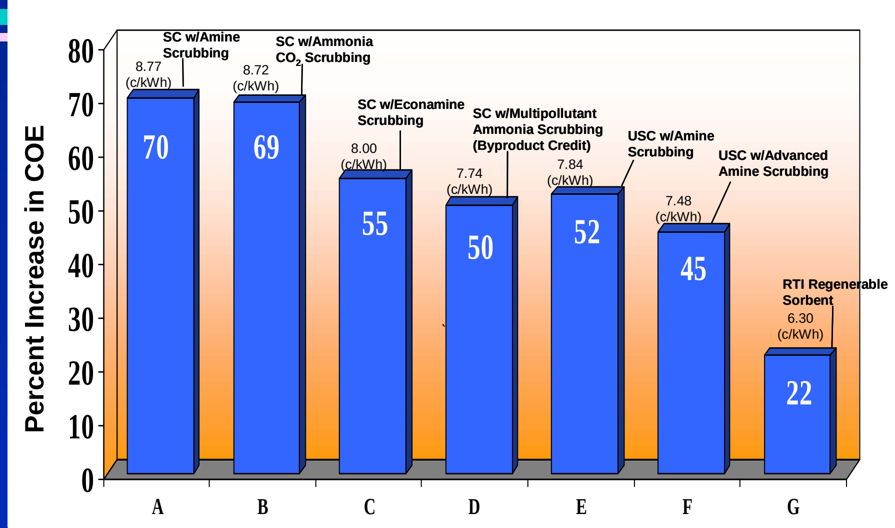
- *Method 1*: Engineering-Economic Analysis
  - A "bottom up" approach based on engineering process models, informed by judgments regarding potential improvements in key process parameters

Latest Projections by DOE/NETL

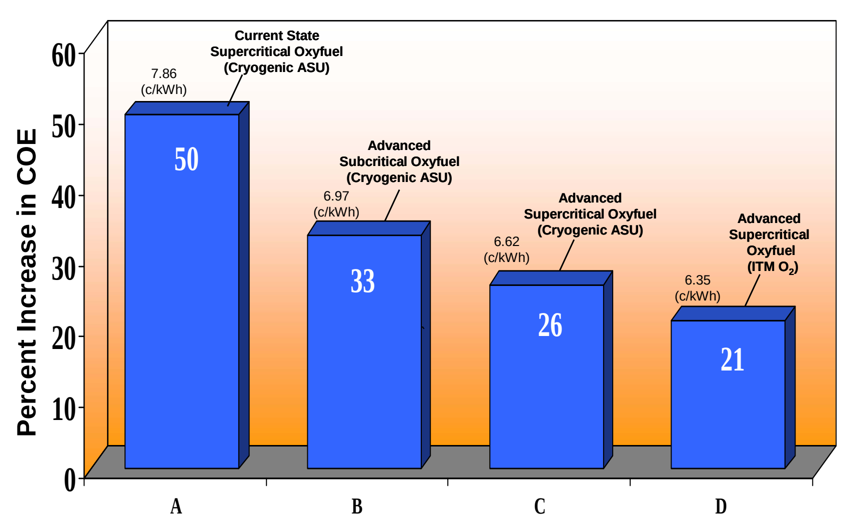
Latest Analyses for IGCC



Latest Analyses for PC Plants



Latest Analyses for Oxy-Combustion



Source: DOE Office of Fossil Energy, 2006

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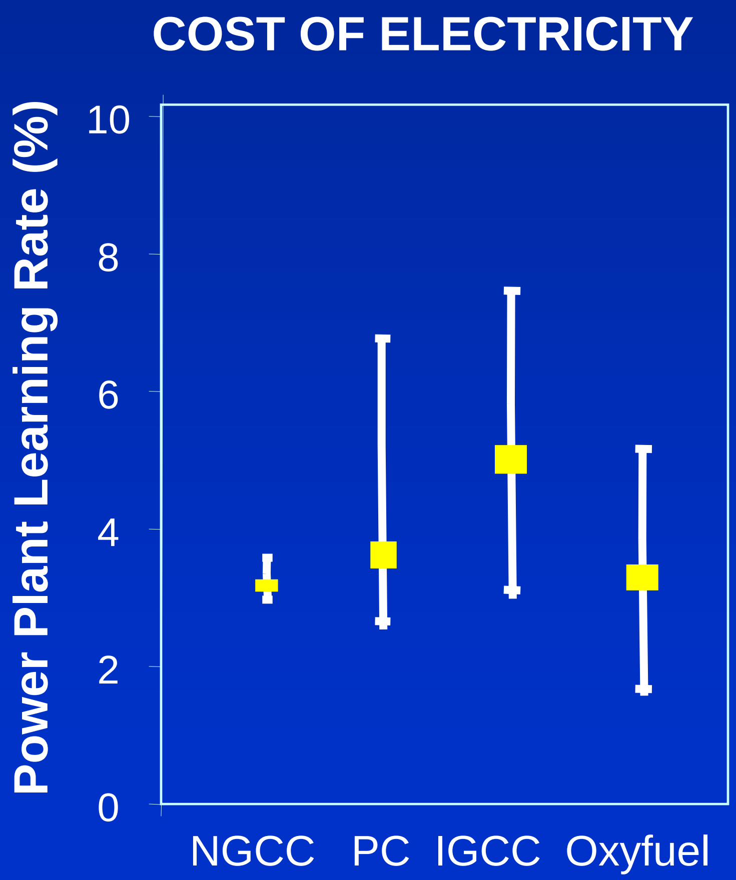
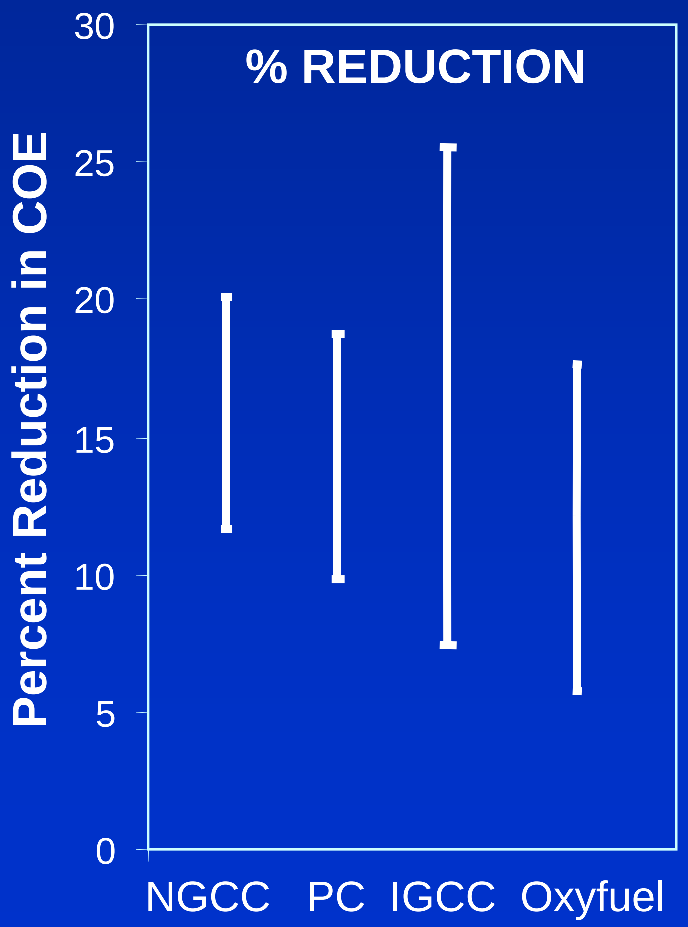
Two Approaches to Estimating Future Technology Costs

- *Method 2:* Use of Historical Experience Curves
  - A "top down" approach based on applications of mathematical "learning curves" or "experience curves" that reflect historical trends for analogous technologies or systems

Estimated Learning Rate for CCS Plants

(Based on 100 GW of cumulative CCS capacity for each system)





Source: IEA GHG, 2006

What are the key needs to develop improved technology?

Key Needs

- Deployment, deployment, deployment !
- Sustained (and increased) R&D support
- Resolution of current legal and institutional uncertainties surrounding geological sequestration
  - Regulatory requirements (esp.for deep injection)
  - Liabilities (near-term and long-term)
  - Financing and insurance requirements
  - Emissions allowance & trading rules for CCS projects

Concluding Comments

- Absent a climate policy with sufficiently stringent limits on CO_2 emissions, there is little or no incentive to develop and deploy CO_2 capture and storage technologies
- Market-based policies aimed broadly at reducing CO_2 emissions (e.g., cap-and-trade) are not likely to stimulate CCS until carbon price exceeds roughly \$100/tC (\$27/tCO_2)
- Policies aimed specifically at fossil fueled plants (e.g., performance and/or portfolio standards) can accelerate CCS deployment and innovation, <u>especially in conjunction with incentives for early actors</u>
- Analysis of options is underway by a number of parties; the ACT Work Group can contribute significantly to this effort

Thank You

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