Indiana Center for Coal Technology Research

Technologies for CO_2 Capture From Electric Power Plants

CCTR Basic Facts File #4

Brian H. Bowen, Marty W. Irwin

The Energy Center at Discovery Park
Purdue University
CCTR, Potter Center, 500 Central Drive
West Lafayette, IN 47907-2022
http://www.purdue.edu/dp/energy/CCTR/
Email: cctr@ecn.purdue.edu

Revised March 2008

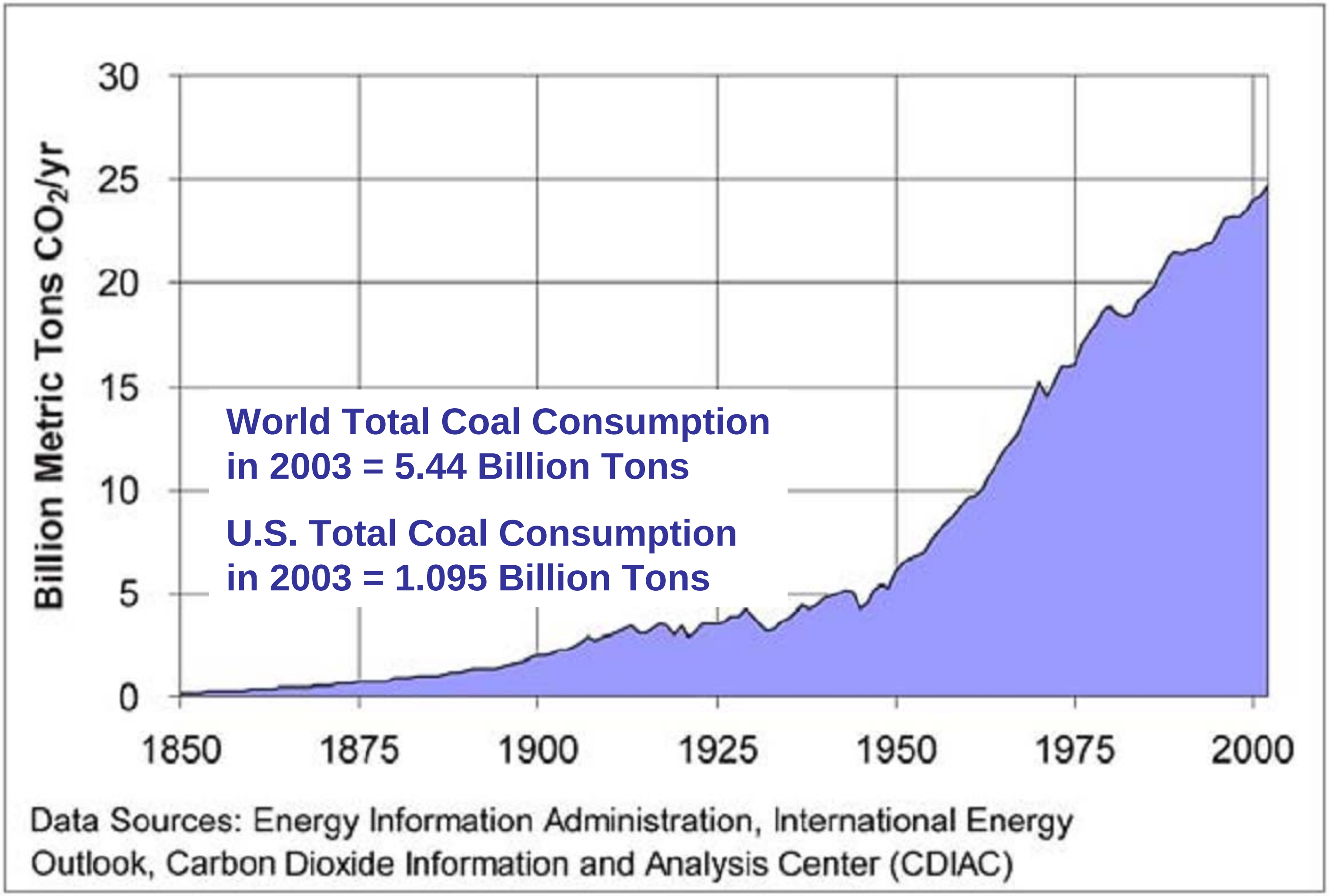
U.S. Department of Energy (DOE)
Carbon Sequestration Program

OBJECTIVE:

"To capture by 2012 fossil fuel conversion systems that offer 90% CO_2 capture with 99% storage permanence at less than a 10% increase in the cost of energy services"

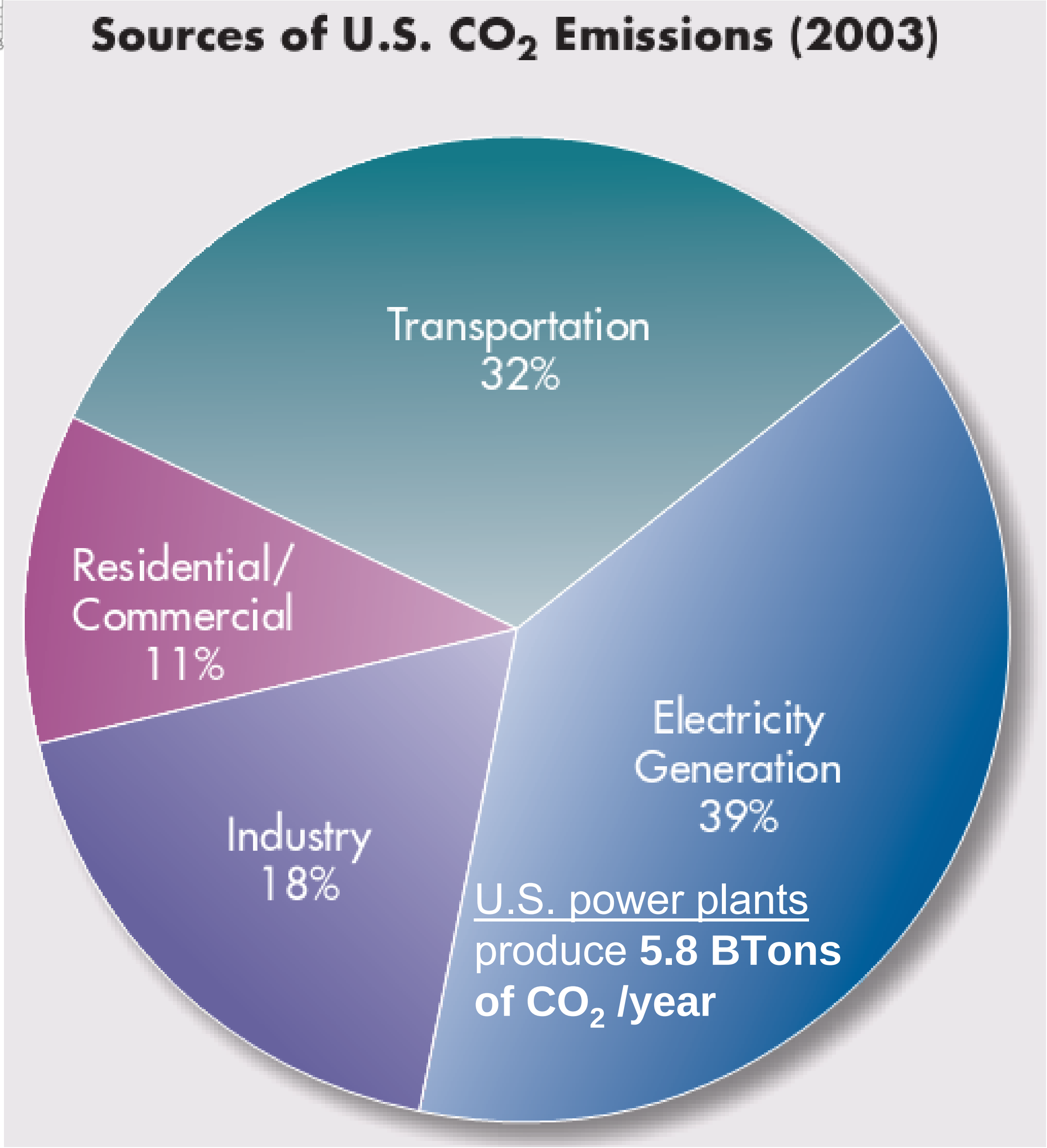
Source: http://www.fossil.energy.gov/programs/sequestration/publications/programplans/2006/2006_sequestration_roadmap.pdf

Worldwide CO_2 Emissions from Fossil Fuel Combustion & Cement Manufacture (BTons/year)



http://www.eia.doe.gov/oiaf/ieo/pdf/ieoreftab_6.pdf

Source: http://www.fossil.energy.gov/programs/sequestration/publications/programplans/2006/2006_sequestration_roadmap.pdf



Affordable technologies need to be developed that can capture CO_2 & use it commercially or safely store it away from the environment for centuries. Ultimate goal is to enable power generators to continue using available coal to provide adequate, secure, affordable electricity as the industry develops economic "CO_2-free" alternatives. Currently "clean coal" technologies appear the least costly & most secure national energy supply for electricity generation

Source: EPRI 2006, http://mydocs.epri.com/docs/CorporateDocuments/EPRI_Journal/2006-Summer/1013720_ClimatePolicy.pdf

CO_2 Emission Factors

EPA CO_2 Emissions Factors

207 lbs per MBtu for **coal**
168 lb per MBtu **oil**
117 lb per MBtu **natural gas**

EPRI guideline

150 Tons of CO_2 /day for 10 MW power plant

Babcock & Wilcox

Modern coal-fired plant with 9000Btu/hr heat rate will produce about **1800 lb of CO_2 per MWh**

Source: "Coal Energy Systems", Bruce G. Miller, 2005, p.376
http://www.iea.org/textbase/papers/2003/CO2_Power_Fossil_Fuels.pdf

CO_2 Emission Factors for Coal

Different rank coals produce different amounts of lbs CO_2 per MBtu

In pounds of CO_2 per Million Btu
U.S. average factors (EIA):

227.4 lbs/MBtu for **anthracite**
216.3 lbs/MBtu for **lignite**
211.9 lbs/MBtu for **sub-bituminous coal &**
205.3 lbs/MBtu for **bituminous coal** (IN 203.6)

Indiana Coal = 22.2 MBtu/Ton
≈ 2.28 Tons CO_2 per Ton Coal

Souce: http://www.eia.doe.gov/cneaf/coal/quarterly/co2_article/co2.html

CO_2 & MWh per Ton Coal for Indiana

Indiana Coal:

203.6 lbs CO_2 per MBtu & 2.28 Tons CO_2 per Ton Coal

2006 Indiana electricity generated = 110,000,000 MWh
2006 Coal consumed for power = 60,582,000 Tons

Indiana average MWh per Ton coal used
= 1.82 MWh per Ton Coal (110,000,000/60,582,000)

1 Ton Coal produces 2.28 Tons CO_2 & 1.82 MWh
& so 1MWh of power produces about 1.25 Tons of CO_2

http://www.eia.doe.gov/cneaf/coal/page/acr/table26.html
http://www.eia.doe.gov/cneaf/electricity/epm/table1_6_a.html

Typical Coal-Fired Power Plant Emissions

Species	Amount emitted (kg/MWh)	Examples of control technology applied
CO_2	830	Amine scrubbers
$NO + NO_X$	2.16	Staging, low-NO_X burners, SCR, SNCR
SO_2	0.6	Wet and dry FGD processes
Particulates	0.1	Electrostatic precipitators, bag filters, cyclones, hot gas cleanup systems

Sources: http://www.iea.org/textbase/papers/2003/CO2_Power_Fossil_Fuels.pdf

The Combustion Process

Combustion is the conversion of a substance called a ***fuel*** into chemical compounds known as ***products of combustion*** by combination with an ***oxidizer*****.** The combustion process is an *exothermic* chemical reaction, i.e., a reaction that releases energy as it occurs. Combustion may be represented by:

High temperature & pressure

Fuel + Oxidizer → Products of combustion + Energy

Emissions of CO_2, SO_2 , Ash

Combustion of a Simple Fuel

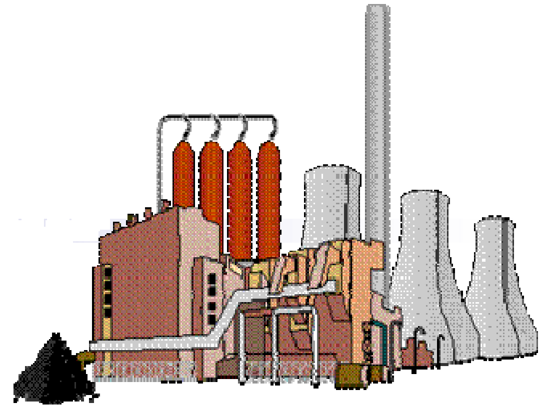
Methane, CH_4, is a common fuel & a major constituent of most natural gases. Consider combustion of methane in pure oxygen. The chemical reaction equation may be written as:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Atoms are neither created nor destroyed. Methane consists of 1 atom of carbon & 4 atoms of hydrogen. It reacts with 4 atoms of oxygen to yield carbon dioxide & water products with the same number of atoms of each *element* as in the reactants

Carbon dioxide is the product formed by complete combustion of carbon through the reaction $C + O_2 \rightarrow CO_2$

CO_2 Emissions from Power Plants



U.S. power plants produce **2.5 Billion Tons of CO_2 /year**

Indiana power plants produce **0.148 Billion Tons CO_2 /year**

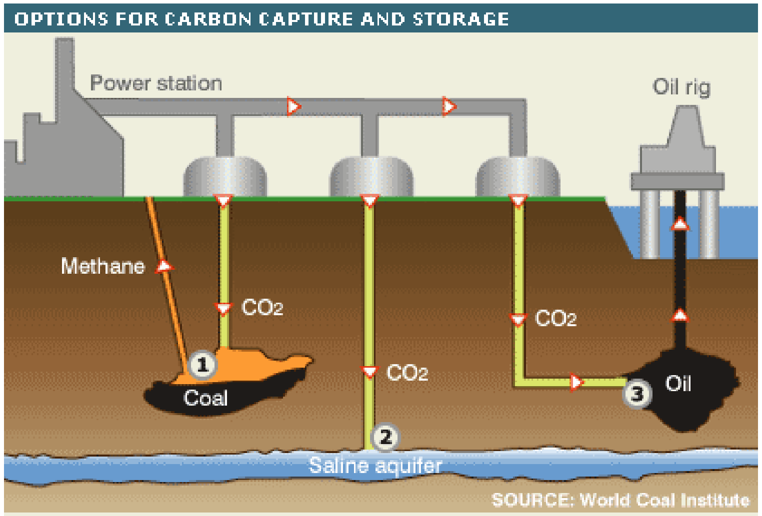
CO_2 Emissions in 2002 & 2003
In the **U.S. rose about 1%**
& in **China rose at 8-9% per year**

2005 concentrations rose 0.5% to 379 PPM
CO_2 remains in the atmosphere for hundreds of years

Source: P.Williams, G.Pavlovicz, Babcock & Wilcox Technical Paper, "Flue Gas Treatment System Design Considerations for the City of Hamilton (Ohio) Oxygen Firing Demonstration", Presented to EPRI-DOE-EPA-AWMA, August 28-31, 2006, Baltimore

Power Plant CO_2 Capture & Storage

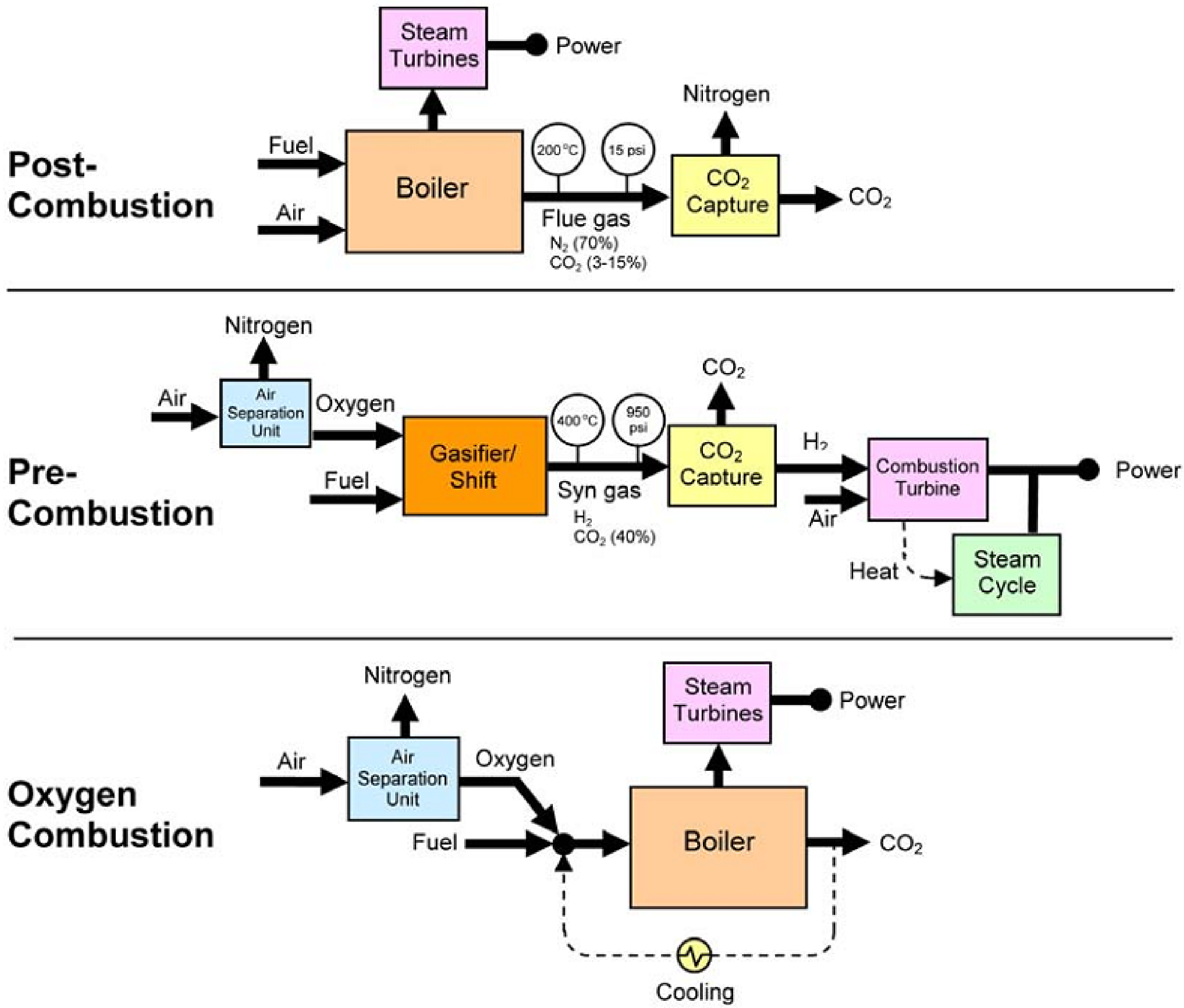
<u>CO_2 can be captured by</u>:
- ***Amine scrubbing***
  - *~ Post combustion*
- ***IGCC power plants***
  - *~ Pre combustion*
- ***Oxygen combustion***
  - *~ Oxyfuel*



1. CO2 pumped into disused coal fields displaces methane which can be used as fuel
2. CO2 can be pumped into and stored safely in saline aquifers
3. CO2 pumped into oil fields helps maintain pressure, making extraction easier

<u>CO_2 can be stored in</u>:
- *Coal fields*
- *Saline aquifers*
- *Oil fields*

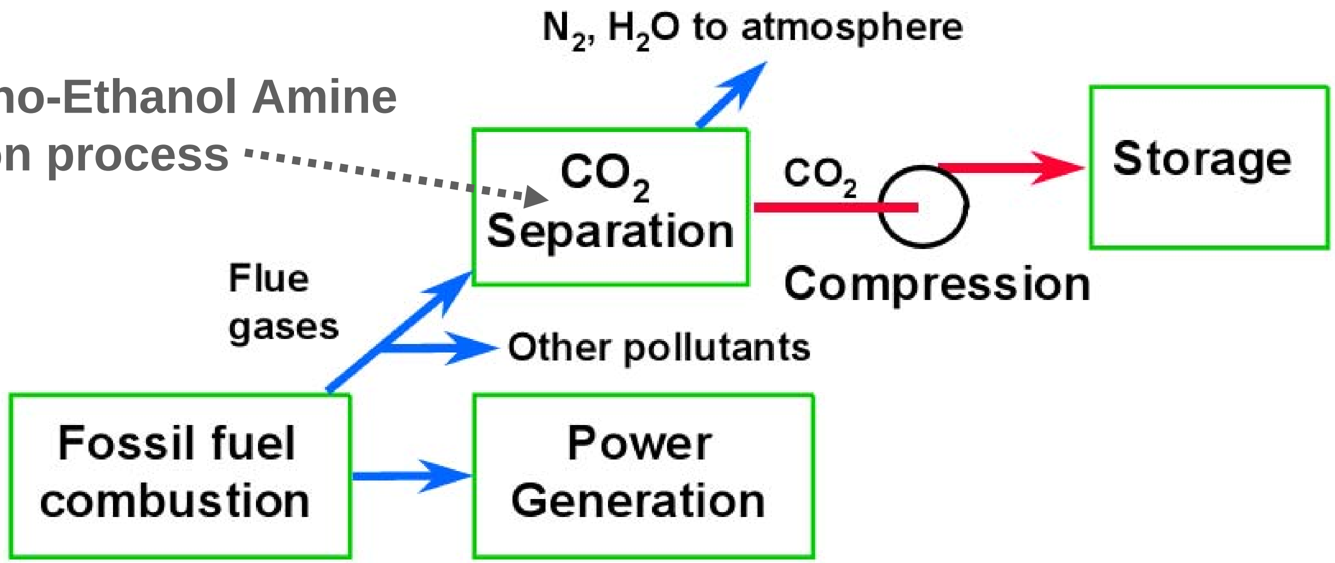
Main Processes for CO_2 Capture



Source: http://www.fossil.energy.gov/programs/sequestration/publications/programplans/2006/2006_sequestration_roadmap.pdf

Post Combustion Capture, Amine Scrubbing

MEA, Mono-Ethanol Amine absorption process



Amines - Any of a class of nitrogen- containing organic compounds derived from ammonia NH_3

CO_2 capture & storage using amine-based scrubbers, the only proven process to date, can consume up to a third of the plant's power output & increase the cost of electricity by 60% to 80%.

Source: http://en.wikipedia.org/wiki/Amide, http://arch.rivm.nl/env/int/ipcc/docs/css2002/ccs02-kt.pdf
EPRI & Nexant, http://www.co2captureandstorage.info/docs/capture/M-Rhudy.pdf

CO_2 Capture by Amine Scrubbing, Costs

Over 75% of the cost & energy drain is due to the capture process (including compression & transportation to the disposal site)

Pilot-scale tests & modeling efforts show that operating an amine stripper at a vacuum can provide a 5-10% reduction in energy use per unit of CO_2 captured

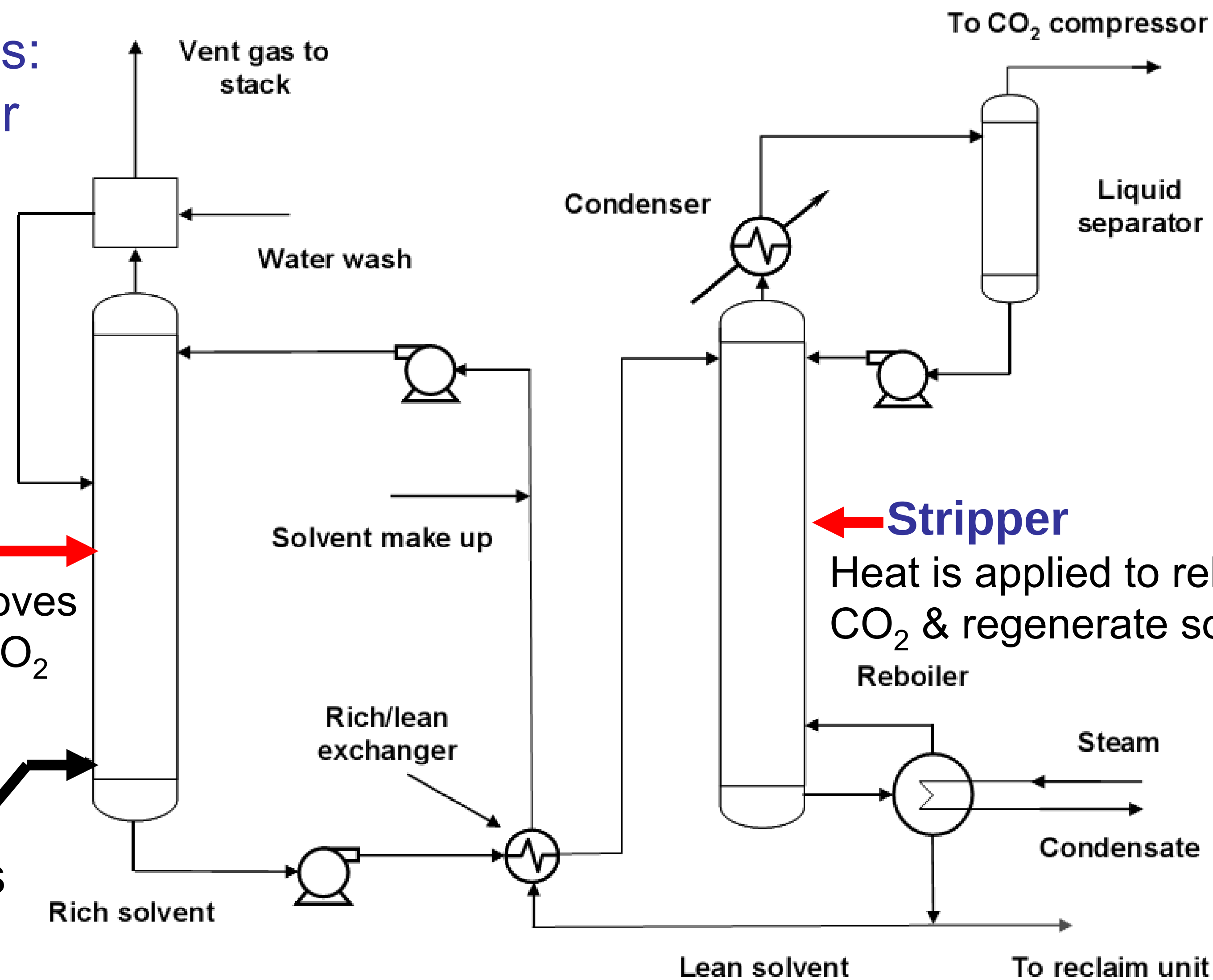
Amine scrubbers with CO_2 compressions to 1200psi costs $2000/kW & reduces the net power output by 12.5%

The cost of **CO_2 capture, is on the order of $150 per ton of carbon - much too high** for carbon emissions reduction applications. Adding existing technologies for CO_2 capture to an electricity generation process **will considerably increase the cost of electricity depending on the type of process**

Sources: http://www.fossil.energy.gov/programs/sequestration/publications/programplans/2006/2006_sequestration_roadmap.pdf
Bruce G. Miller "Coal Energy Systems, 2005

Post Combustion CO_2 Gas Treatment Process

Two stages:
- Absorber
- Stripper



Absorber
Solvent removes majority of CO_2 by chemical absorption

Flue Gas

Stripper
Heat is applied to release the CO_2 & regenerate solvent

Source: EPRI, John Wheeldon et al, "Post-Combustion CO_2 Capture from Pulverized Coal Plants"

Post Combustion - Chilled Ammonia Process 2006 Process Cost Prediction by EPRI

Used Parsons Study for basis	Supercritical PC without CO_2 Removal	Supercritical PC with MEA CO_2 Removal	Supercritical PC with NH_3 CO_2 removal
Levelized cost of Power, c/KWh	5.15	8.56	6.50
% increase		66	26
Avoided Cost, $/ton CO_2	Base	51	20

PC - Pulverized Coal

MEA - Mono-Ethanol Amine

CO_2 - Carbon Dioxide

NH_3 - Ammonia

NH_3 is extensively used to manufacture fertilizers & a wide variety of nitrogen-containing organic & inorganic chemicals

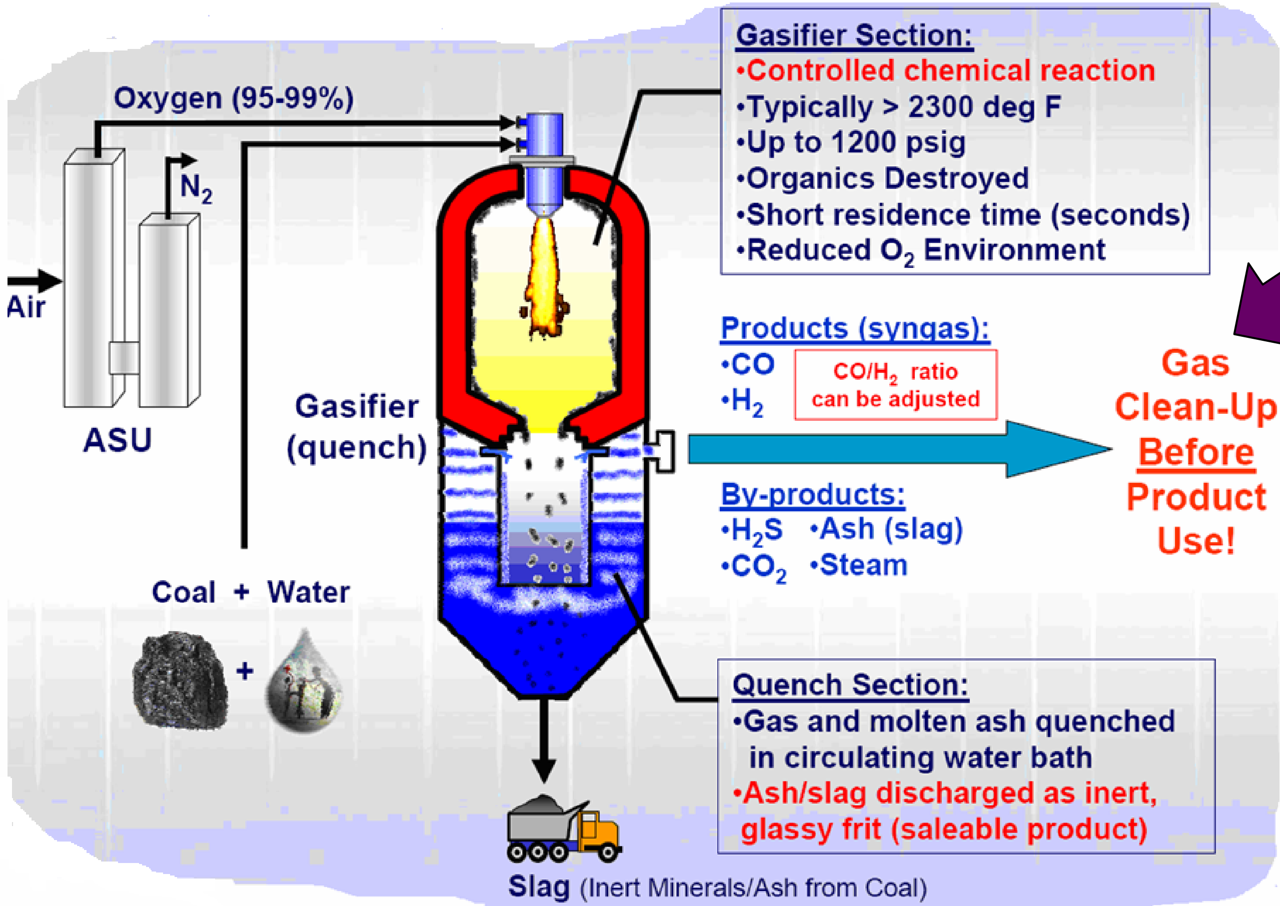
Source: EPRI & Nexant, http://www.co2captureandstorage.info/docs/capture/M-Rhudy.pdf

Chilled Ammonia
2006 Process Performance Prediction

Used Parsons Study for Basis	Supercritical PC Without CO_2 Removal	Supercritical PC With MEA CO_2 Removal	Supercritical PC With NH_3 CO_2 Removal
LP Steam extraction, lb/hr	0	1,220,000	270,000
Power Loss, KWe	0	90,000	20,000
GROSS POWER, KWE	491,000	402,000	471,300
AUXILIARY LOAD, KWE			
Induced Draft Fan	5,000	19,900	10,000
Pumping CO_2 system,	0	1,900	5,000
Chillers	0	0	8,900
CO_2 compressor	0	30,000	9,500
NET POWER OUTPUT	462,000	330,000	415,000
% POWER REDUCTION		29	10

Source: EPRI & Nexant, http://www.co2captureandstorage.info/docs/capture/M-Rhudy.pdf

Pre Combustion Process
CO_2 Capture by IGCC Power Plants



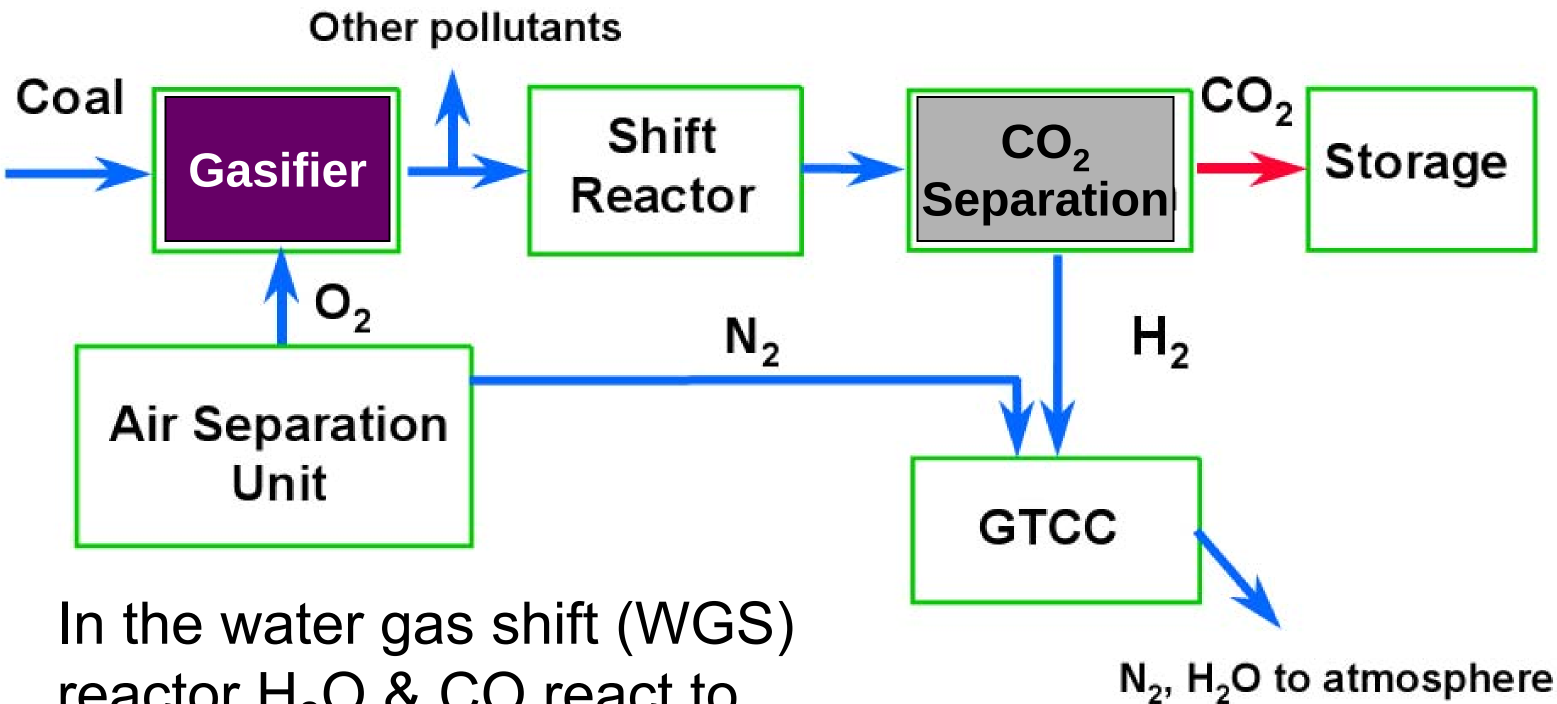
CO_2 capture

EPRI:
In 2000 the IGCC process was cheaper than post combustion CO_2 capture but all technologies are now improving

IGCC – Integrated Gasification Combined Cycle

Source: EPRI, John Wheeldon et al, "Post-Combustion CO_2 Capture from Pulverized Coal Plants"

Pre Combustion Process
CO_2 Capture by IGCC Power Plants



In the water gas shift (WGS) reactor H_2O & CO react to form CO_2 & H_2 (water splitting)

Source: http://arch.rivm.nl/env/int/ipcc/docs/css2002/ccs02-kt.pdf

EPRI 2003 Cost of Electricity with Pre & Post Combustion CO_2 Capture – 4 Plants & 2 Coals

Technology	Pittsburg #8	Sub-bituminous
Texaco quench **IGCC**	$56.3/MWh	$62.2/MWh
SC PC	61.7	60.4
USC PC	57.0	56.2
USC PC + X	47.5	46.6

IGCC Integrated Gasification Combined Cycle

– Pre combustion CO_2 capture

SC PC Supercritical Pulverized Coal Plant

– Post combustion CO_2 capture with sterically-hindered amines

USC PC Ultra-supercritical Pulverized Coal Plant with Double Reheat

– Post combustion CO_2 capture with sterically-hindered amines

USC PC + X Ultra-supercritical Pulverized Coal Plant with Double Reheat

\- Post combustion CO_2 capture with ammonium carbonate & improved boiler

Costs of IGCC & other technologies are changing

Source: EPRI, John Wheeldon et al, “Post-Combustion CO_2 Capture from Pulverized Coal Plants”, Table 5, page 14”

CCTR

Oxyfuel, An Emerging Technology

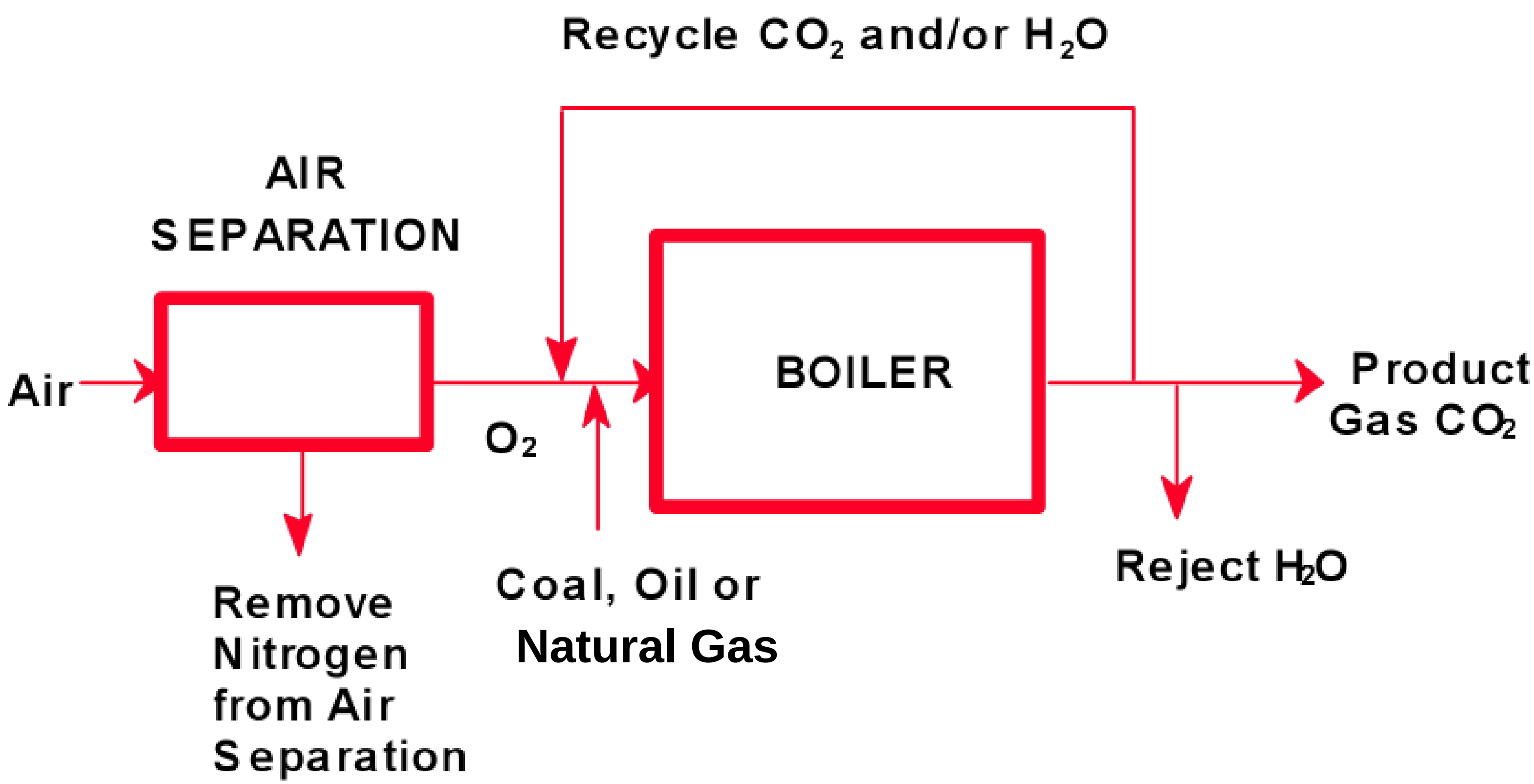
Oxyfuel combustion is an emerging technology that has the potential to allow for **control of CO_2 emissions at a low cost.** Oxyfuel combustion involves replacing air with pure oxygen in a pulverized coal boiler. The use of O_2 results in **a lower volume of flue gas** with a much **higher concentration of CO_2.**

Combusting coal in pure O_2 **results in temperatures that are too high** for existing boiler and turbine materials. Part of the CO_2 rich flue gas is recycled to the boiler to reduce the exhaust temperature.

The **cost of carbon capture** in an oxyfuel power plant **should be lower** than for a conventional air-fired PC plant, as a result of the decreased flue gas volume and increased concentration of CO_2. However, these advantages are offset, to some extent, by the cost of providing oxygen and the cost of the recycle compressor.

Source: NETL, Southern Research Institute

Oxyfuel
CO_2 Capture by Oxygen Combustion



In such a power generation application the resulting effluent is a CO_2 rich flue gas (up to 98% vol., dry) that can be removed for utilization of disposal with minimum additional flue gas treatment

Source: http://www.netl.doe.gov/publications/proceedings/98/98ps/ps4-4.pdf

Oxyfuel
CO_2 Capture by Oxygen Combustion

Using O_2 instead of air during the combustion process produces **a flue gas that is 90% pure CO_2** & is already at low pressure (10-15psi). However this requires three times more O_2 per kWh of electricity generation than gasification

No oxyfuel PC power plants are in commercial operation in the U.S.

Processes & tests for developing Oxyfuel technology:

* Advanced combustion in mixtures of O_2 & recycled flue gas
* Burners that incorporate a membrane to extract O_2 from air
* How to lower the cost of retrofit systems

Source: “Coal Energy Systems”, Bruce G. Miller, 2005, p.378

CO_2 Capture/Storage Status

All current methods of CO_2 separation/capture cause an additional high energy demand which results from the actual separation, the regeneration of solvents, the poorer efficiency of the core process, & the energy required for the compression & drying of the CO_2 into a transportable & storable state. Advances are being made in assessing the economics of various methods for large scale commercialization

CO_2 capture costs for retrofitting existing coal-fired power plants represent an approximate increase of 20% to 40% in the cost of electricity

Source: http://www.isi.fhg.de/publ/downloads/isi06b46/CO2-captures-storage.pdf
http://www.ingentaconnect.com/content/els/01968904/2003/00000044/00000019/art00040

Oxyfuel Retrofits for Existing PC Boilers

Recovering CO_2 from the flue gas at a PC-fired boiler will significantly increase the cost of electricity. The main reasons are that the **volume of gas is very large** & the **concentration of CO_2 is low**, (< 15%). Commercially available absorption processes, such as amine based systems, require large vessels & consume considerable parasitic power. **Development of oxyfuel technology will simplify carbon capture** in PC-fired power plants by minimizing the volume of flue gas produced & vastly increasing the CO_2 concentration, thereby significantly reducing CO_2 capture cost. **Successfully retrofitting oxyfuel technology into existing PC power plants should enable CO_2 capture goals to be met at a lower costs than constructing all new facilities**.

Source: NETL, Southern Research Institute

CO_2 Capture/Storage Summary

There is no zero-emission power station, only low-emission power stations. In installations with post-combustion or pre-combustion CO_2 capture, the capture rates could be between 85% and 95% of the emitted CO_2

The additional costs for the control of CO_2 from power stations are significant. **Additional technology for CO_2 capture & compression/storage could result in over 50% increases in the cost of electricity.** With future improvements in technology the capital costs for CO_2 controls should decrease

Source: http://www.isi.fhg.de/publ/downloads/isi06b46/CO2-captures-storage.pdf