Sixth Annual Conference on Carbon Capture & Sequestration

Steps Toward Deployment

CCS Economic Analyses

Outlook for Carbon Capture from Pulverized Coal and Integrated Gasification Combined Cycle Power Plants

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Analyses Conducted Across Various Energy Technologies

New construction
CO_2 Capture Ready

Retrofit Existing Plants
Co-sequestration

Coal Gasification (IGCC)

Selexol
H_2/ CO_2 Membrane
Chemical Looping
Solid & Liquid Sorbents

Pulverized Coal

Amine Scrubbing
Ammonia Scrubbing
Solid Sorbents
CO_2 Membrane

Oxyfuel Combustion

Cryogenic Air Sep. Unit
O_2 Membranes
Compact Boilers
Advanced Steam Cycles
Chemical Looping

Pathways to Zero Emissions

CO_2 Capture from Fossil Energy Power Plants

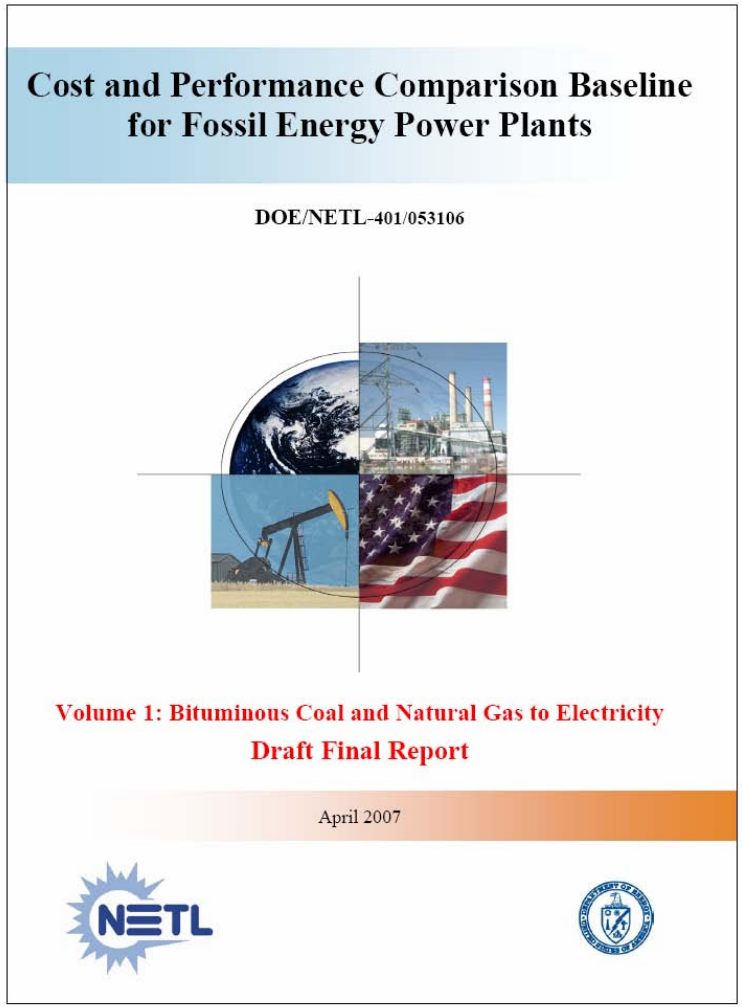
-Report Contains-

Subcritical Pulverized Coal

Supercritical Pulverized Coal

Integrated Gasification Combined Cycle

Natural Gas Combined Cycle



Study Matrix

Plant Type	ST Cond. (psig/°F/°F)	Gasifier/ Boiler	Acid Gas Removal/ CO_2 Separation / Sulfur Recovery	CO_2 Cap
IGCC	1800/1050/1050 (non-CO_2 capture cases) 1800/1000/1000 (CO_2 capture cases)	GE Energy	Selexol / - / Claus	
			Selexol / Selexol / Claus	90%
		ConocoPhillips (E-Gas)	MDEA / - / Claus	
			Selexol / Selexol / Claus	88%[1]
		Shell	Sulfinol-M / - / Claus	
			Selexol / Selexol / Claus	90%
PC	2400/1050/1050	Subcritical	Wet FGD / - / Gypsum	
			Wet FGD / Econamine / Gypsum	90%
	3500/1100/1100	Supercritical	Wet FGD / - / Gypsum	
			Wet FGD / Econamine / Gypsum	90%

[1] CO_2 capture is limited to 88% by syngas CH_4 content

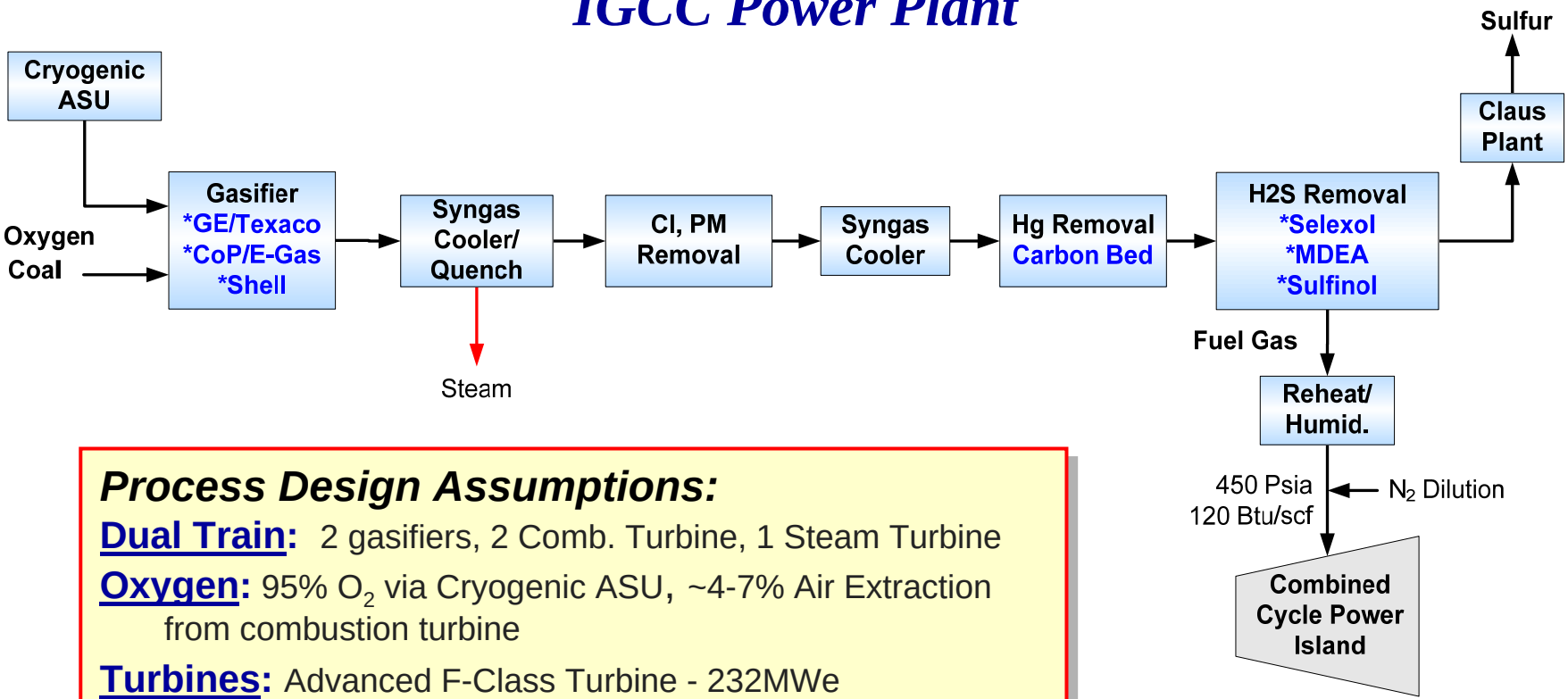
Economic Assumptions

Startup	**2012**
Plant Life (Years)	**20**
Capital Charge Factor	
High Risk	
(All IGCC, PC/NGCC with CO_2 capture)	**17.5**
Low Risk	
(PC/NGCC without CO_2 capture)	**16.4**
Dollars (Constant)	**2007**
Coal ($/MM Btu)	**1.80**
Capacity Factor	
IGCC	**80**
PC/NGCC	**85**

IGCC Power Plant

Current State
with and without CO_2 Capture

Current Technology
IGCC Power Plant



Process Design Assumptions:

Dual Train: 2 gasifiers, 2 Comb. Turbine, 1 Steam Turbine

Oxygen: 95% O_2 via Cryogenic ASU, ~4-7% Air Extraction from combustion turbine

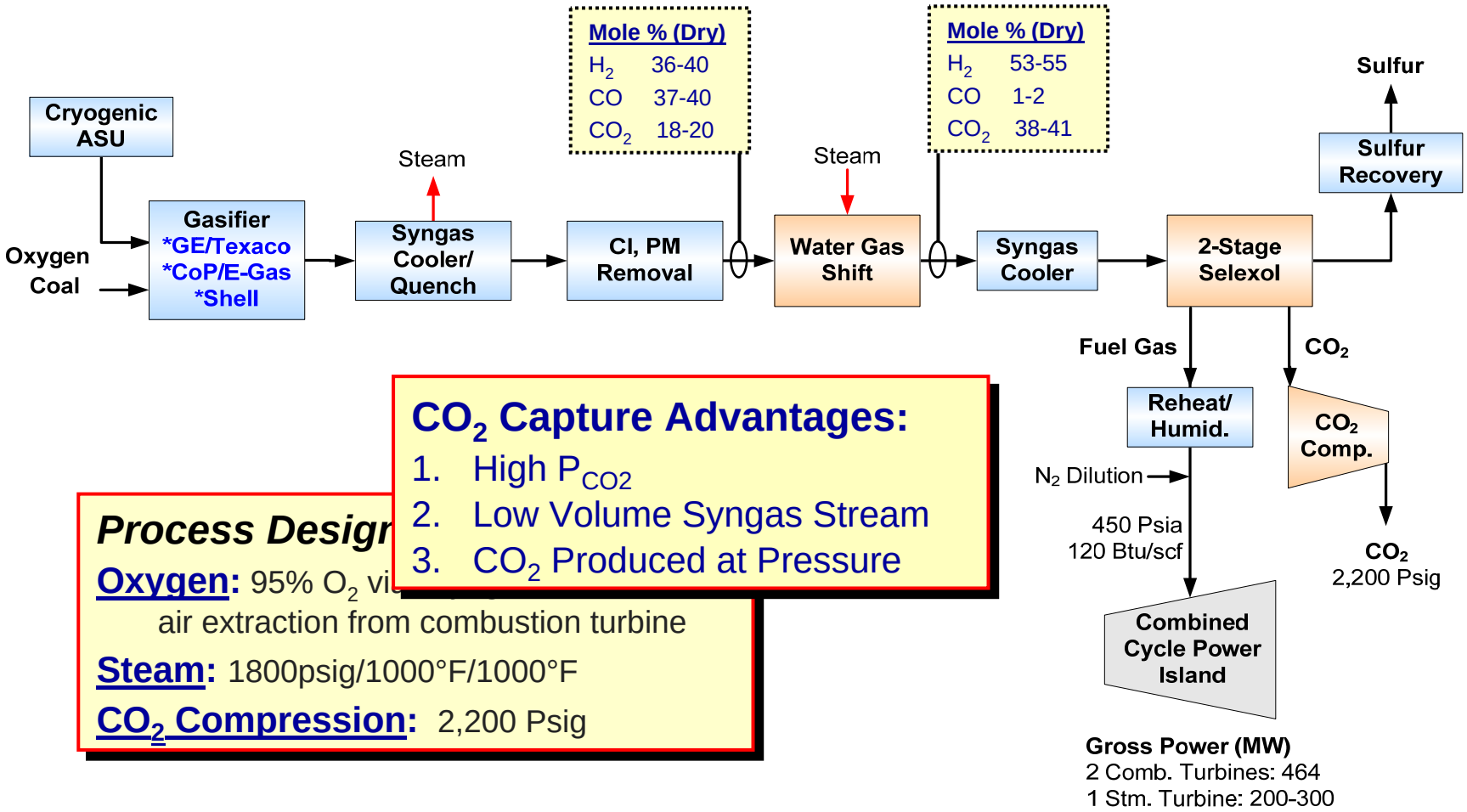
Turbines: Advanced F-Class Turbine - 232MWe
N_2 dilution employed to full extent in all cases
Humidification/steam injection used only when necessary to meet syngas specification of ~120 Btu/scf LHV

Steam: 1800psig/1050°F/1050°F

Cost and Performance Comparison Baseline for Fossil Energy Power Plants, U.S. Department of Energy—National Energy Technology Laboratory, Draft Final Report, May 2007

Pre-Combustion Current Technology

IGCC Power Plant with CO_2 Scrubbing



CO_2 Capture Advantages:

1. High P_{CO2}
2. Low Volume Syngas Stream
3. CO_2 Produced at Pressure

Process Desigr

Oxygen: 95% O_2 vi
air extraction from combustion turbine

Steam: 1800psig/1000°F/1000°F

CO_2 Compression: 2,200 Psig

Cost and Performance Comparison Baseline for Fossil Energy Power Plants, U.S. Department of Energy—National Energy Technology Laboratory, Draft Final Report, May 2007

GE Energy IGCC Performance Results

	GE Energy	
CO_2 Capture	**NO**	**YES**
Gross Power (MW)	**770**	**745**
Auxiliary Power (MW)		
Base Plant Load	23	23
Air Separation Unit	103	121
Gas Cleanup/CO_2 Capture	4	18
CO_2 Compression	-	27
Total Aux. Power (MW)	130	189
Net Power (MW)	640	556
Heat Rate (Btu/kWh)	8,922	10,505
Efficiency (HHV)	**38.2**	**32.5**
Energy Penalty[1]	**-**	**5.7**

Steam for WGS, Selexol Unit

↑ in ASU air comp. load w/o turbine integration

Includes H_2S/CO_2 Removal in Selexol Solvent

[1]CO_2 Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO_2 Capture

Cost and Performance Comparison Baseline for Fossil Energy Power Plants, U.S. Department of Energy—National Energy Technology Laboratory, Draft Final Report, May 2007

IGCC Performance Summary

	GE Energy		E-Gas		Shell	
CO_2 Capture	NO	YES	NO	YES	NO	YES
Gross Power (MW)	**770**	**745**	**742**	**694**	**748**	**693**
Auxiliary Power (MW)						
Base Plant Load	23	23	25	26	21	19
Air Separation Unit	103	121	91	109	90	113
Gas Cleanup/CO_2 Capture	4	18	3	15	1	16
CO_2 Compression	-	27	-	26	-	28
Total Aux. Power (MW)	**130**	**189**	**119**	**176**	**112**	**176**
Net Power (MW)	**640**	**556**	**623**	**518**	**636**	**517**
Efficiency (%HHV)	**38.2**	**32.5**	**39.3**	**31.7**	**41.1**	**32.0**
Energy Penalty[1]	**-**	**5.7**	**-**	**7.6**	**-**	**9.1**

[1] CO_2 Capture Energy Penalty = Percent points decrease in net power plant efficiency due to CO_2 Capture

CO_2 Capture decreases net efficiency by ~5-9 percentage points

IGCC Economic Results Summary

	GE Energy		E-Gas		Shell	
CO_2 Capture	NO	YES	NO	YES	NO	YES
Plant Cost ($/kWe)						
Base Plant	1,323	1,566	1,272	1,592	1,522	1,817
Air Separation Unit	287	342	264	329	256	336
Gas Cleanup/CO_2 Capture	203	414	197	441	199	445
CO_2 Compression	-	68	-	69	-	70
Total Plant Cost ($/kWe)	**1,813**	**2,390**	**1,733**	**2,431**	**1,977**	**2,668**
Capital COE (¢/kWh)	4.53	5.97	4.33	6.07	4.94	6.66
Variable COE (¢/kWh)	3.27	3.94	3.19	4.08	3.11	3.97
Total COE (¢/kWh)	**7.80**	**9.9**	**7.52**	**10.2**	**8.05**	**10.6**
Increase in COE (%)	**-**	**27**	**-**	**35**	**-**	**32**

IGCC CO_2 capture results in:
Increase in Capital Cost (TPC) ~ $577—691/kW
Increase in COE ~2.1—2.6 cents/kWh (~ ↑30%)

IGCC with CO_2 Capture Key Points

1. **Gasifier design (dry feed vs. slurry, quench vs. heat exchanger) has large influence on water-gas shift steam requirement, steam turbine output and net plant efficiency**

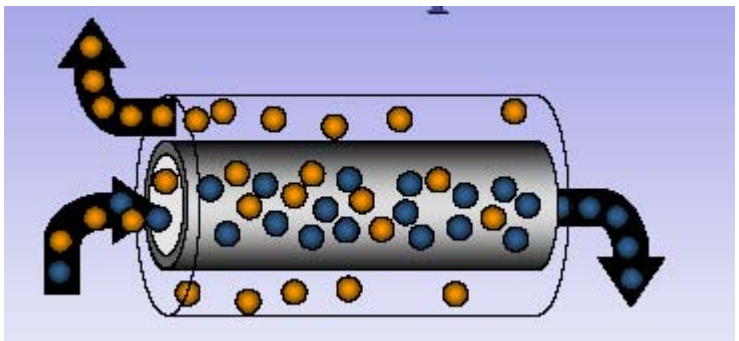
2. **<u>Average</u> COE without CO_2 capture = 7.8 cents/kWh**

3. **<u>Average</u> COE with CO_2 capture = 10.2 cents/kWh**

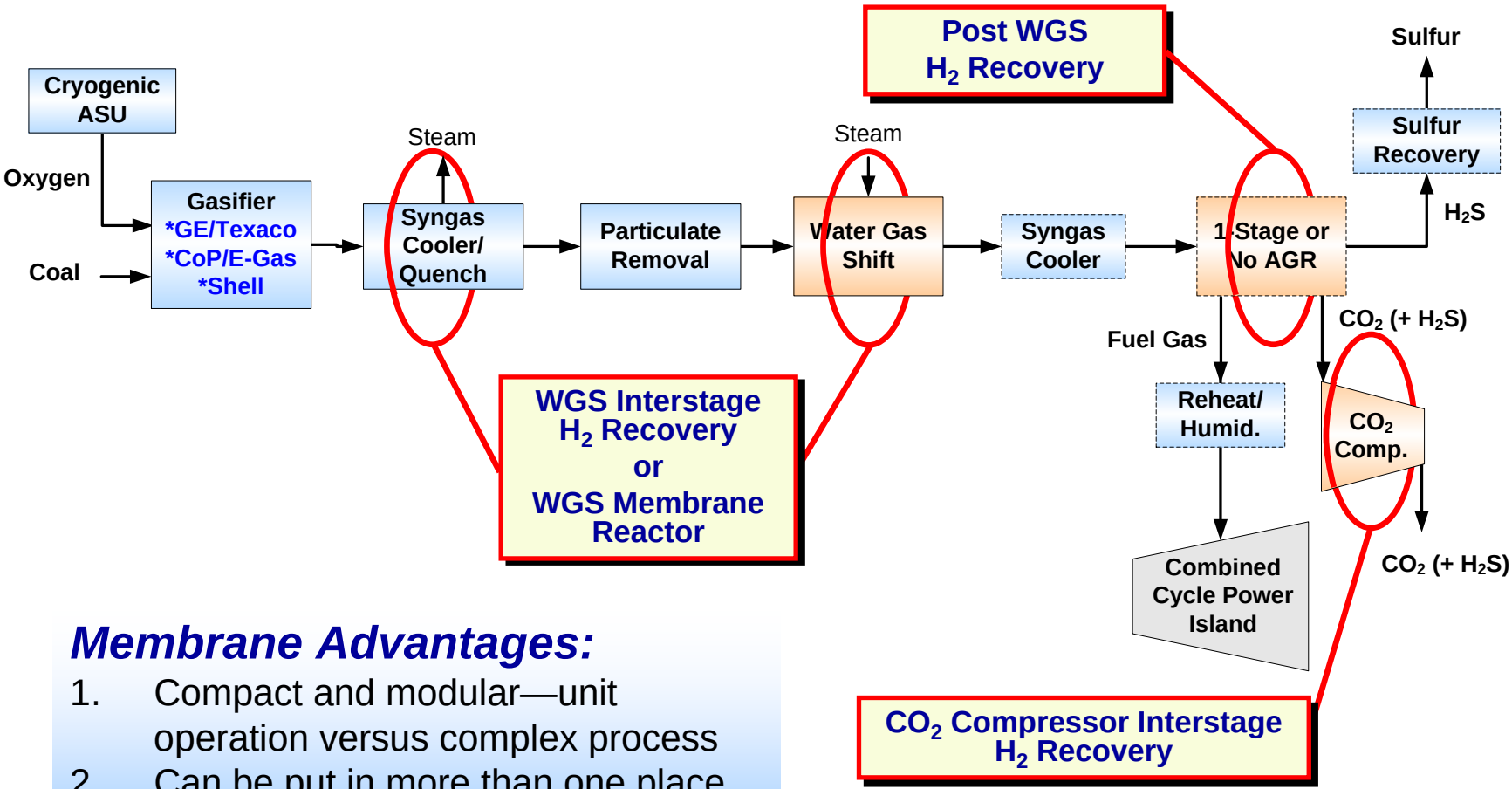
4. **<u>Average</u> CO_2 mitigation cost = \$26/ton CO_2 removed (\$33/ton CO_2 avoided)**

Technology Options to Decrease IGCC CO_2 Capture Costs

Example
Gas Separation Membranes



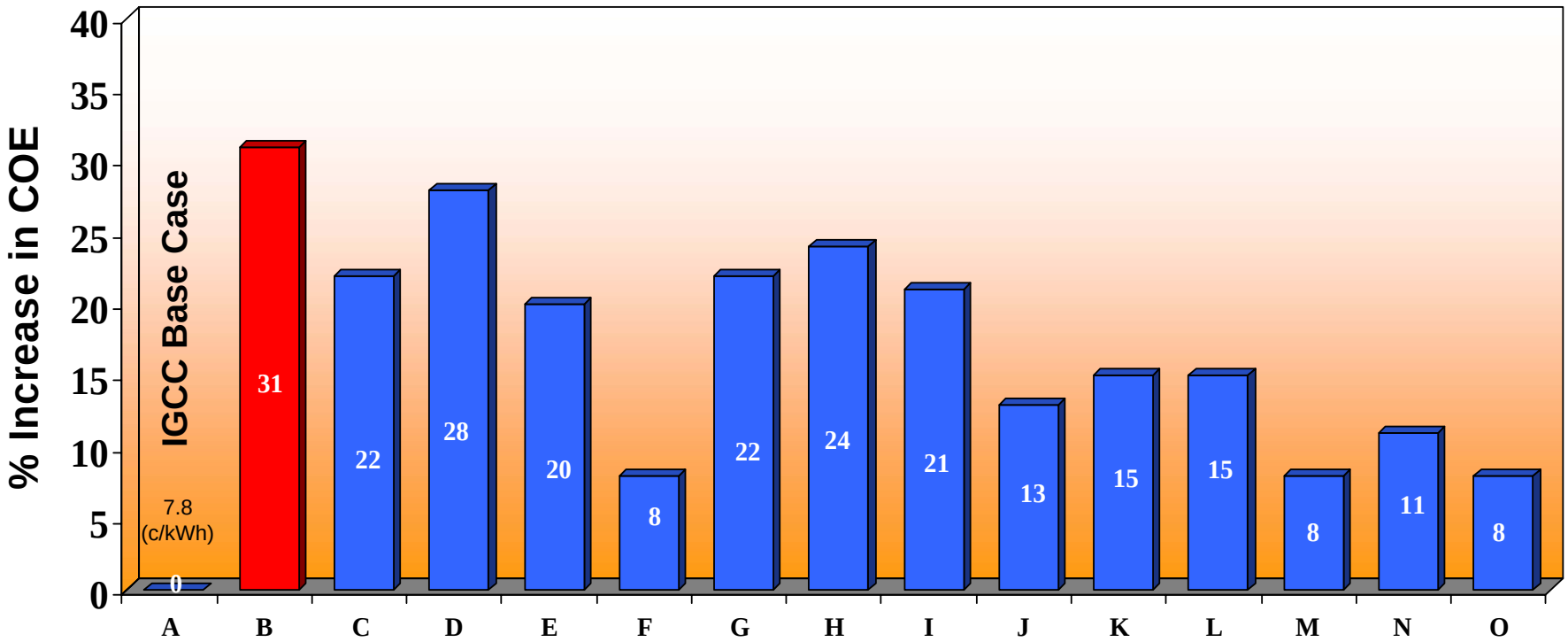
Possible Integrations of Membranes into IGCC Plant



Membrane Advantages:

1. Compact and modular—unit operation versus complex process
2. Can be put in more than one place
3. Produce CO_2 at pressure
4. Opportunities for Co-capture

CO_2 Capture Economics for IGCC



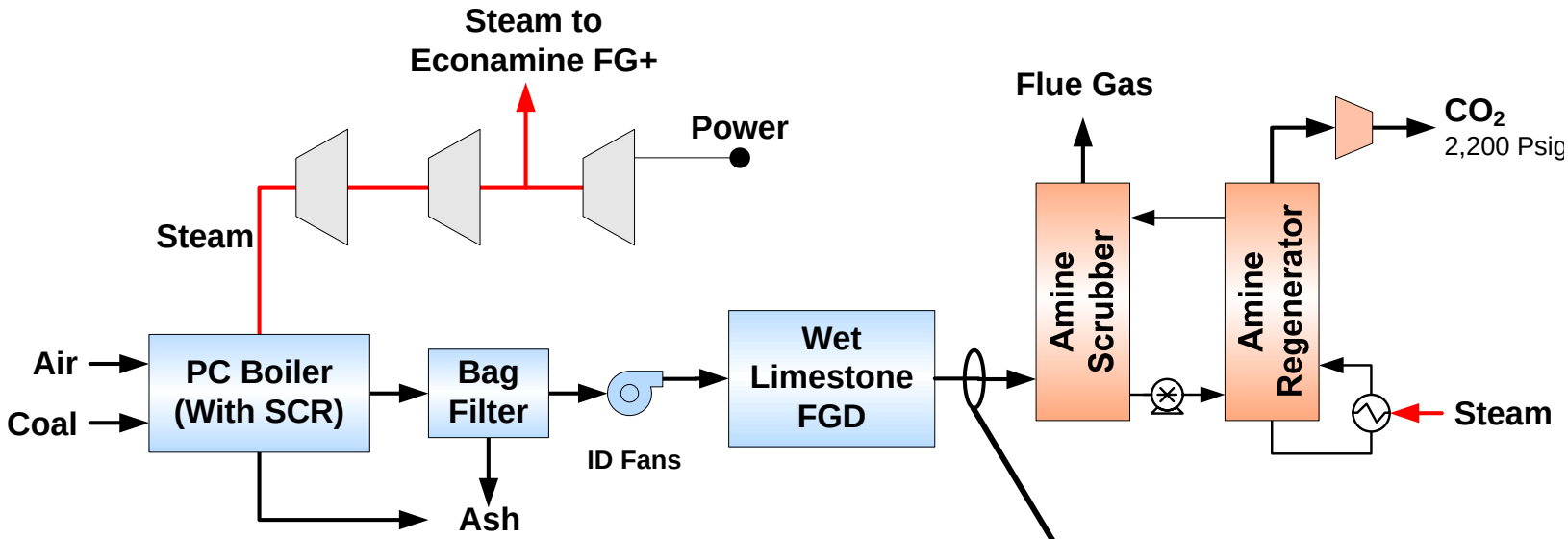
A—IGCC w/o CO_2 Capture
B—Selexol Scrubbing
C—Advanced Sorbent Scrubbing
D—Selexol w/ Co-Storage of H_2S/CO_2
E—Advanced Sorbent w/ Co-Storage of H_2S/CO_2
F*—Adv. Sorb. + Co-Production + Co-Storage
G—Selexol w/ O_2 Membrane
H—Selexol w/ WGS Membrane
I—Selexol w/ O_2/WGS Membranes
J—Advanced Sorbent w/ O_2/WGS Membranes
K—Advanced Sorbent w/ O2/WGS Membranes, Co-storage
L—Chemical Looping w/ Co-Storage
M—Co-Production w/ H_2 Membrane
N—Co-Production w/ SOFC
O—Co-Production w/ SOFC and H_2 Membrane
*NG at$5.54/MM Btu

Pulverized Coal Power Plant

Current State CO_2 Capture Using Advanced Amines

Post-Combustion Current Technology

Pulverized Coal Power Plant with CO_2 Scrubbing



Process Design Assumptions:

Steam:

Subcritical → 2400psig/1050°F/1050°F

Supercritical → 3500psig/1100°F/1100°F

CO_2 Capture Challenges:

1. Dilute Flue Gas (10-14% CO_2)
2. Low Pressure CO_2
3. 1.5 Million scfm
4. 17,000 ton CO_2/day removed
5. Large Parasitic Loads (Steam + CO_2 Compression)

Subcritical PC Performance

	Subcritical	
Coal Flow Rate	**5,252**	**7,759**
CO_2 Captured (Ton/day)	**0**	**16,566**
Gross Power (MW)	**584**	**681**
Auxiliary Power (MW)		
Base Plant Load	19	36
Forced + Induced Draft Fans	10	14
Flue Gas Cleanup	4	5
CO_2 Capture	-	24
CO_2 Compression	-	52
Total Aux. Power (MW)	**33**	**131**
Net Power (MW)	**550**	**550**
Efficiency (%HHV)	**36.8**	**25.0**
Energy Penalty (% Points)	**-**	**11.8**

48% Increase in Coal Flow Rate

Larger Base Plant

MEA Scrubbing

~17,000 TPD to 2,200 Psig

CO_2 Capture decreases net efficiency by ~12 percentage points

Pulverized Coal Performance Summary

	Subcritical		Supercritical	
Coal Flow Rate	**5,252**	**7,759**	**4,935**	**7,039**
CO_2 Captured (Ton/day)	**0**	**16,566**	**0**	**15,029**
Gross Power (MW)	**584**	**681**	**580**	**664**
Auxiliary Power (MW)				
Base Plant Load	19	36	21	32
Forced + Induced Draft Fans	10	14	9	13
Flue Gas Cleanup	4	5	3	5
CO_2 Capture	-	24	-	21
CO_2 Compression	-	52	-	47
Total Aux. Power (MW)	**33**	**131**	**30**	**118**
Net Power (MW)	**550**	**550**	**550**	**546**
Efficiency (%HHV)	**36.8**	**25.0**	**39.1**	**27.2**
Energy Penalty (% Points)	**-**	**11.8**	**-**	**11.9**

CO_2 Capture decreases net efficiency by ~12 percentage points

Pulverized Coal Economic Results Summary

	Subcritical		Supercritical	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**
Plant Cost ($/kWe)				
Base Plant	1,302	1,689	1,345	1,729
SOx and NOx Cleanup	246	323	229	302
CO_2 Capture	-	792	-	752
CO_2 Compression	-	89	-	85
Total Plant Cost ($/kWe)	**1,548**	**2,893**	**1,574**	**2,868**
Capital COE (¢/kWh)	**3.41**	**6.79**	**3.47**	**6.74**
Variable COE (¢/kWh)	**2.99**	**4.63**	**2.86**	**4.34**
Total COE (¢/kWh)	**6.40**	**11.42**	**6.33**	**11.08**
Increase in COE (%)	**-**	**78**	**-**	**75**

PC CO_2 capture results in:
Increase in Capital Cost (TPC) ~ $1,325/kW
Increase in COE ~5 cents/kWh (~ ↑77%)

Pulverized Coal CO_2 Capture Key Points

1. **Advanced amine scrubbing technology for 90% CO_2 capture continues to be very energy intensive and costly**
   - Definite need for performance and cost improvements

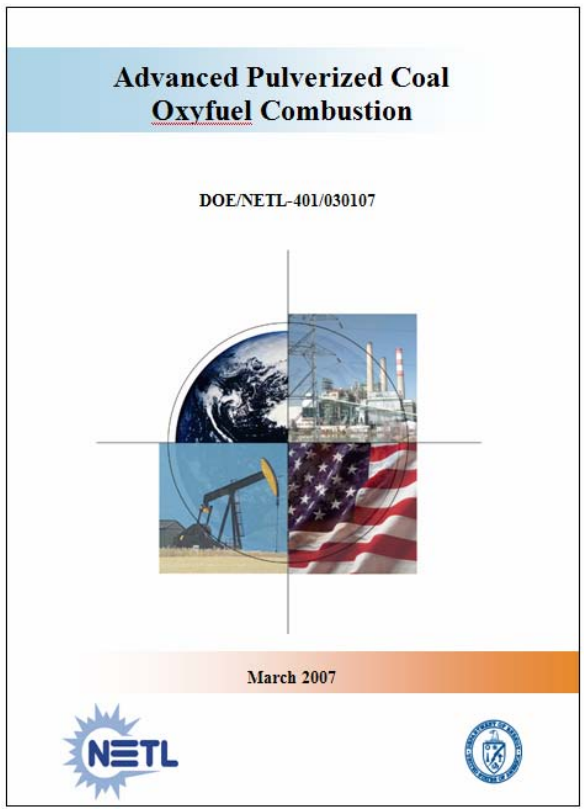
2. **Average COE without CO_2 capture ~ 6.4 cents/kWh (versus 7.8 cents/kWh for IGCC)**

3. **Average COE with CO_2 capture ~11 cents/kWh (versus 10 cents/kWh for IGCC)**

4. **Average CO_2 mitigation cost = $41/ton CO_2 removed ($63/ton CO_2 avoided)**

Technology Options to Decrease Pulverized Coal CO_2 Capture Costs

Example
Oxyfuel Combustion



"Advanced Pulverized Coal Oxyfuel Combustion"

-Report Contains-

Supercritical PC Oxyfuel

Ultra-supercritical PC Oxyfuel

Cryogenic and membrane oxygen

Co-Sequestration (CO_2/SOx)

Pulverized Coal Oxyfuel Combustion

Technology Opportunities

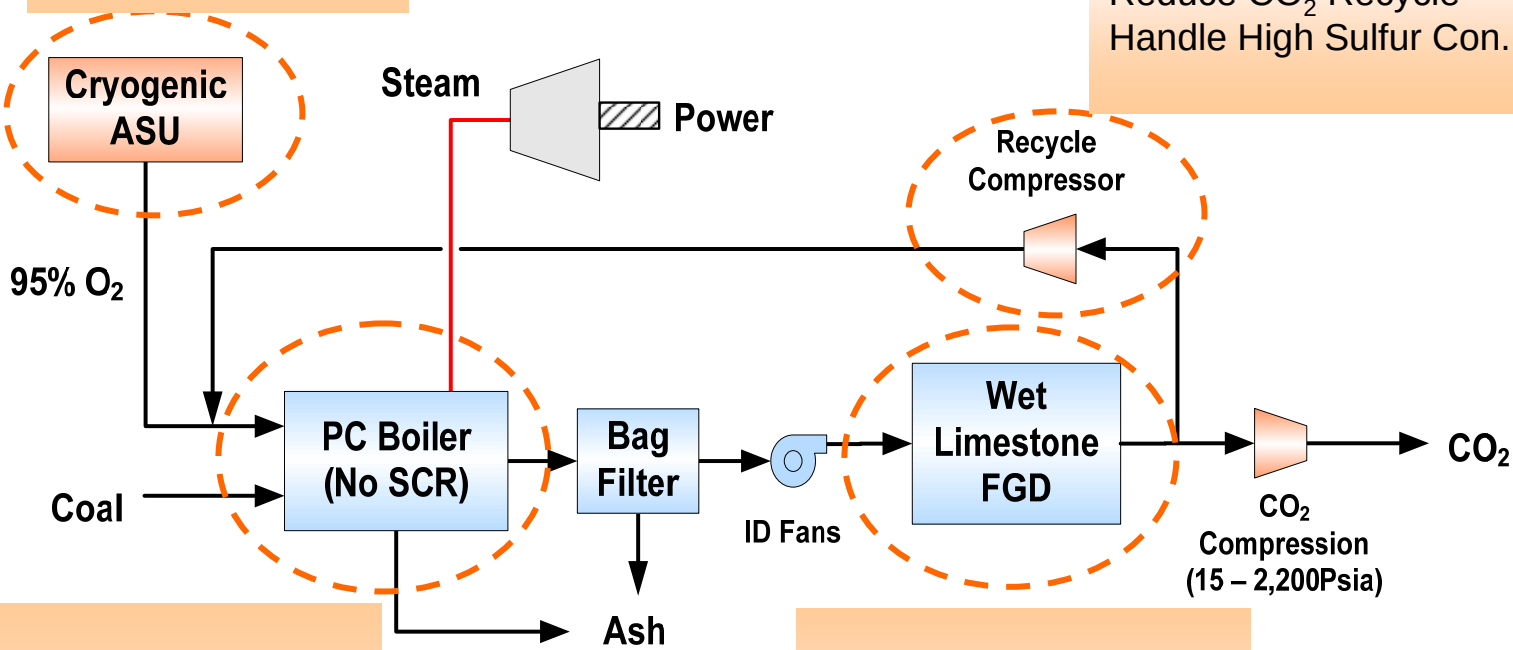
Cheap Oxygen

Oxygen Membran

$$Coal + O_2 \rightarrow CO_2 + H_2O$$

Advanced MOC

Reduce CO_2 Recycle
Handle High Sulfur Con.



Oxyfuel Boilers

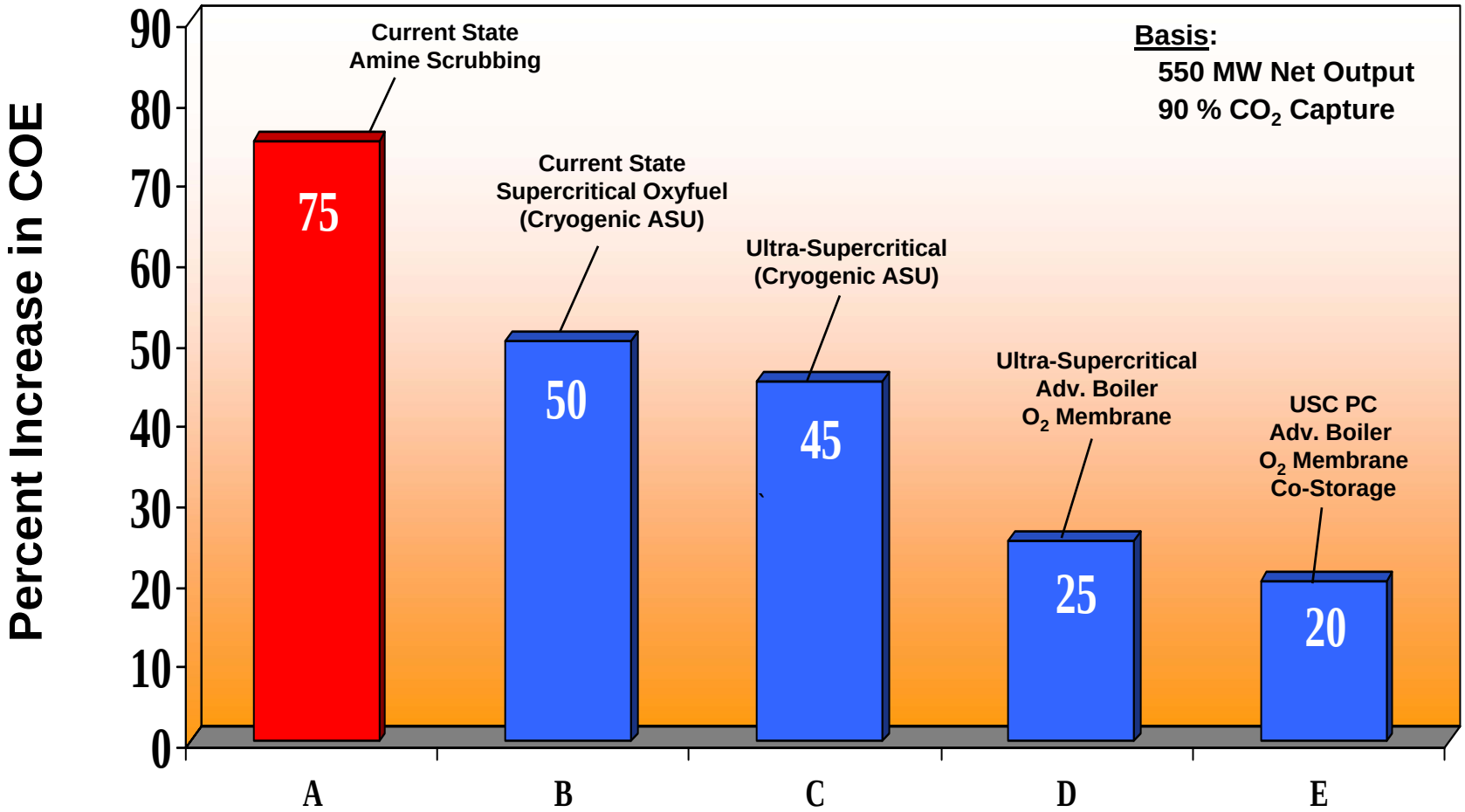
Compact Boiler Designs
Advanced Materials
Advanced Burners

Co-Sequestration

Remove FGD

Foster Wheeler, B&W, Alstom Power, Air Liquide, Air Products

Driving Down Oxyfuel Combustion Costs



Sources:

1. *2007 Pulverized Coal Oxyfuel Combustion Power Plants*, U.S. Department of Energy—National Energy Technology Laboratory, Draft Final Report, April 2007
2. *Conceptual Design of Oxygen Based Pulverized Coal Boiler*, Foster Wheeler North America Corporation, developed for U.S. Department of Energy—National Energy Technology Laboratory, September 2006

Thank You!

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NETL Energy Analysis Link:
www.netl.doe.gov/energy-analyses

Design Basis: Bituminous Coal Type

Illinois #6 Coal Ultimate Analysis (weight %)

	As Rec'd	Dry
Moisture	11.12	0
Carbon	63.75	71.72
Hydrogen	4.50	5.06
Nitrogen	1.25	1.41
Chlorine	0.29	0.33
Sulfur	2.51	2.82
Ash	9.70	10.91
Oxygen (by difference)	6.88	7.75
	100.0	100.0
HHV (Btu/lb)	11,666	13,126

Environmental Targets

	IGCC[1]	PC[2]	NGCC[3]
SO_2	0.0128 lb/MMBtu	0.085 lb/MMBtu	< 0.6 gr S /100 scf
NOx	15 ppmv (dry) @ 15% O_2	0.07 lb/MMBtu	2.5 ppmv @ 15% O_2
PM	0.0071 lb/MMBtu	0.017 lb/MMBtu	Negligible
Hg	> 90% capture	1.14 lb/TBtu	Negligible

[1] Based on EPRI's CoalFleet User Design Basis Specification for Coal-Based IGCC Power Plants
[2] Based on BACT analysis, exceeding new NSPS requirements
[3] Based on EPA pipeline natural gas specification and 40 CFR Part 60