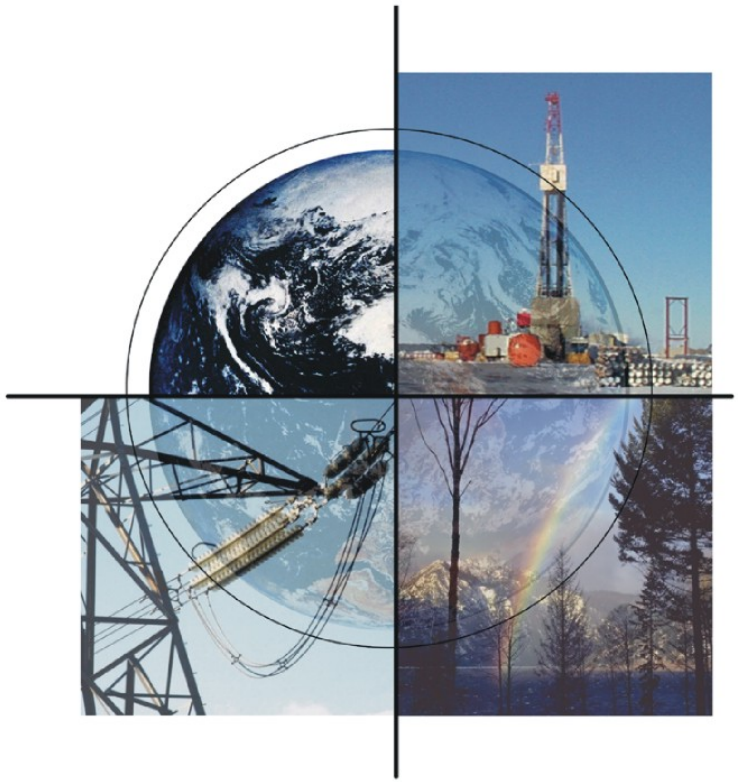
CO_2 Capture: Comparison of Cost & Performance of Gasification and Combustion-based Plants



Workshop on Gasification Technologies

Indianapolis, Indiana

June 12-13, 2007

Jared Ciferno
National Energy Technology Laboratory

Disclaimer

CO_2 Capture from Fossil Energy Power Plants

-Report Contains-

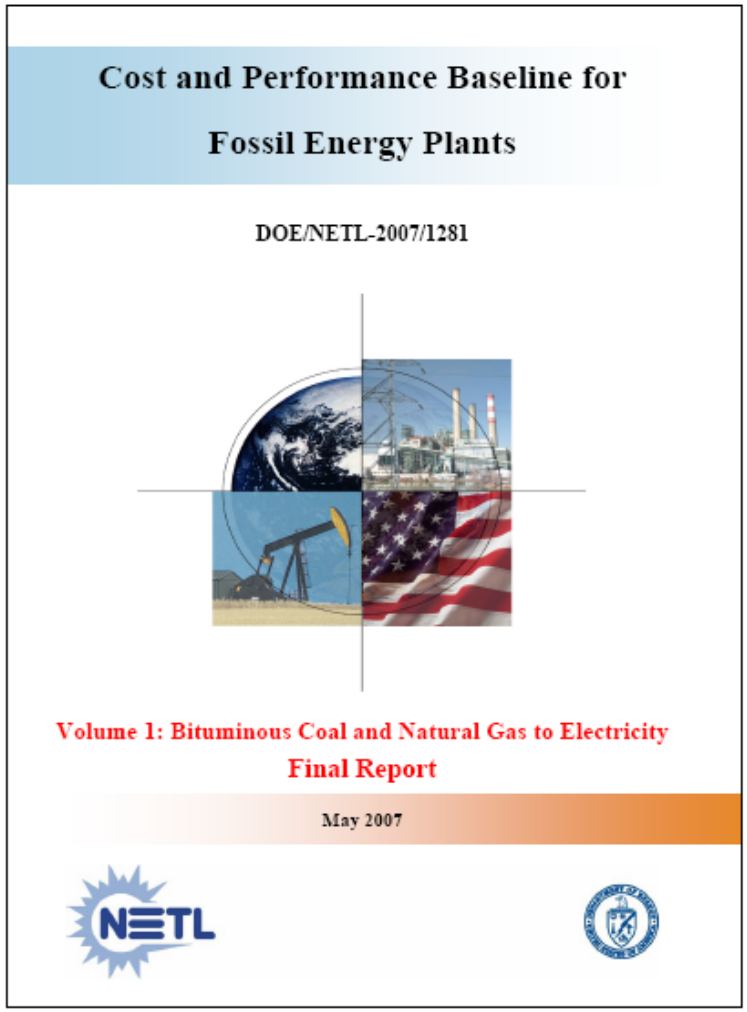
Subcritical PC

Supercritical PC

IGCC

NGCC

- Consistent design requirements
- Up-to-date performance and capital cost estimates
- Technologies built now and deployed by 2010



Study Matrix

Plant Type	ST Cond. (psig/°F/°F)	GT	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)	F Class	GE	Selexol / - / Claus	
				Selexol / Selexol / Claus	90%
			CoP 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%
NGCC	2400/1050/950	F Class	HRSG		
				- / Econamine / -	90%

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

GEE – GE Energy
CoP – Conoco Phillips

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

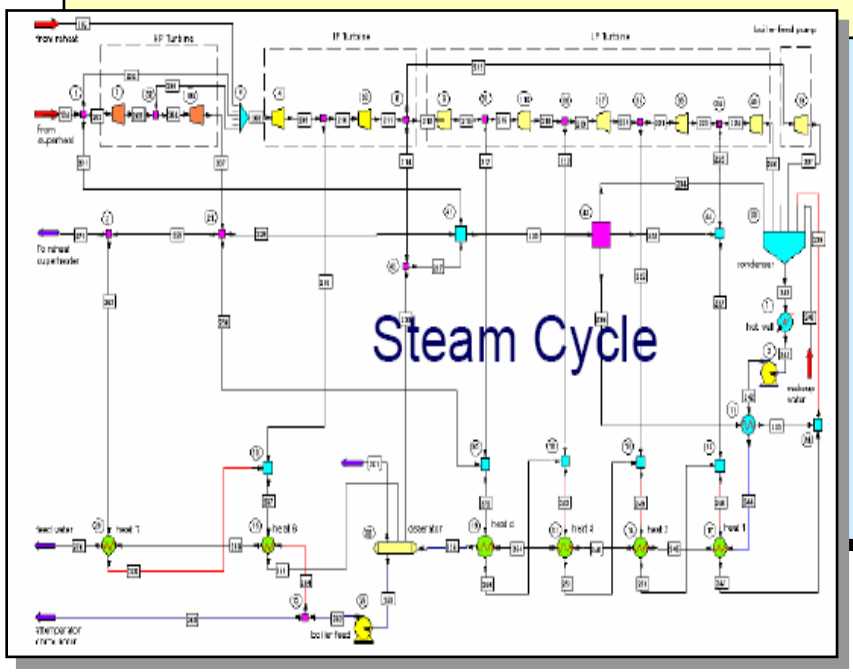
	IGCC[1]	PC[2]	NGCC[3]
SO_2	0.0128 lb/MMBtu	0.085 lb/MMBtu	Negligible
NOx	15 ppmv (dry) @ 15% O_2	0.07 lb/MMBtu	2.5 ppmv @ 15% O_2
PM	0.0071 lb/MMBtu	0.013 lb/MMBtu	Negligible
Hg	> 90% capture	1.14 lb/TBtu	Negligible

[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

Technical Approach

1. Extensive Process Simulation (ASPEN)

- All major chemical processes and equipment are simulated
- Detailed mass and energy balances
- Performance calculations (auxiliary power, gross/net power output)



2. Cost Estimation

- **Inputs from process simulation** (Flow Rates/Gas Composition/Pressure/Temp.)
- **Sources for cost estimation**
  - Parsons
  - Vendor sources where available
- **Follow DOE Analysis Guidelines**

Economic Assumptions

Startup	2010
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 ($/MM Btu)	1.80
Natural Gas ($/MM Btu)	6.75
Capacity Factor	
IGCC	80
PC/NGCC	85

Total Plant Cost

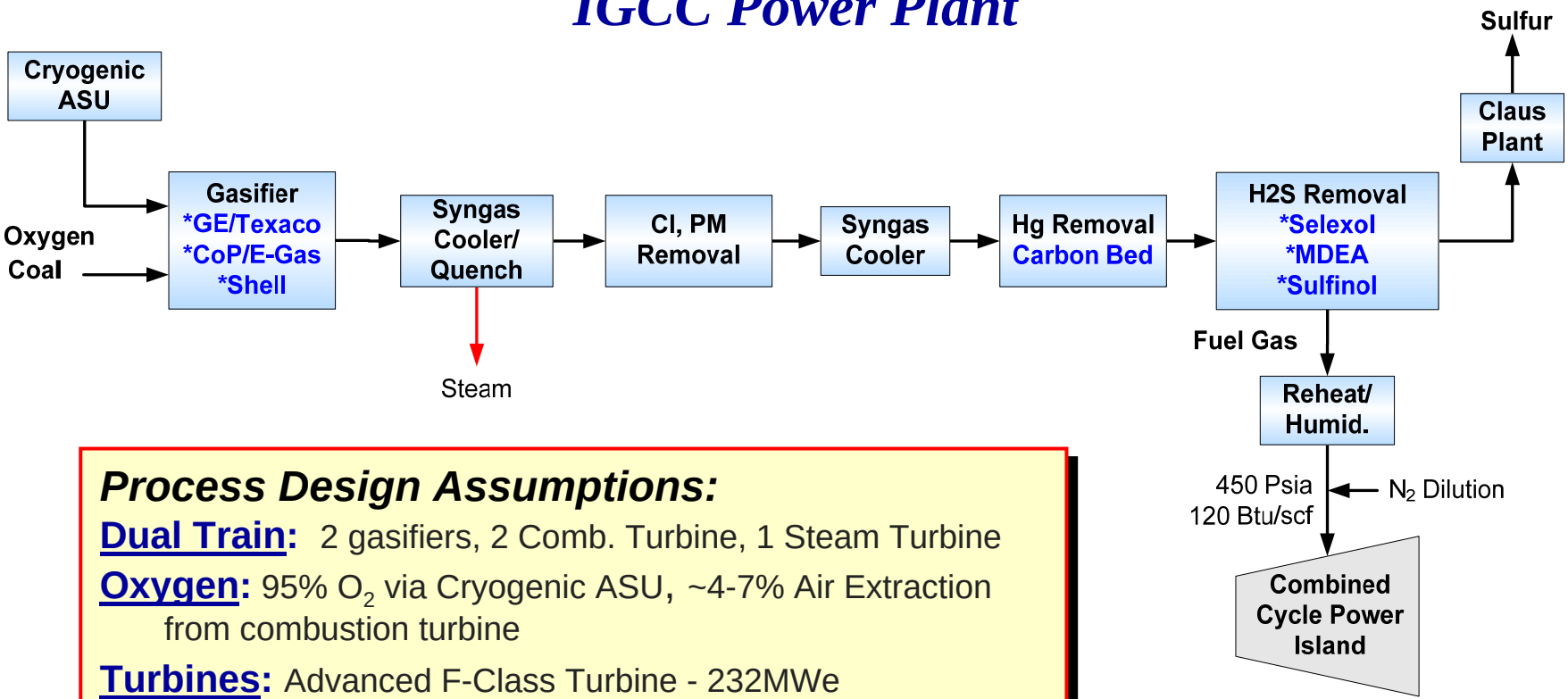
- **Includes**
  - Equipment
    - Initial chemicals and catalyst loadings
  - Materials
  - Labor
    - Direct and Indirect
  - Engineering and Construction Management
  - Project and Process Contingencies

- **Excludes**
  - Owner's costs
    - Land, licensing and permitting, AFUDC
  - Escalation to period of performance
  - Taxes (except payroll)
  - Site specific considerations
  - Labor incentives in excess of 5 day/10 hour work week
  - EPC premiums

IGCC Power Plant

Current State CO_2 Capture Using Selexol

Current Technology
IGCC Power Plant



Process Design Assumptions:

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

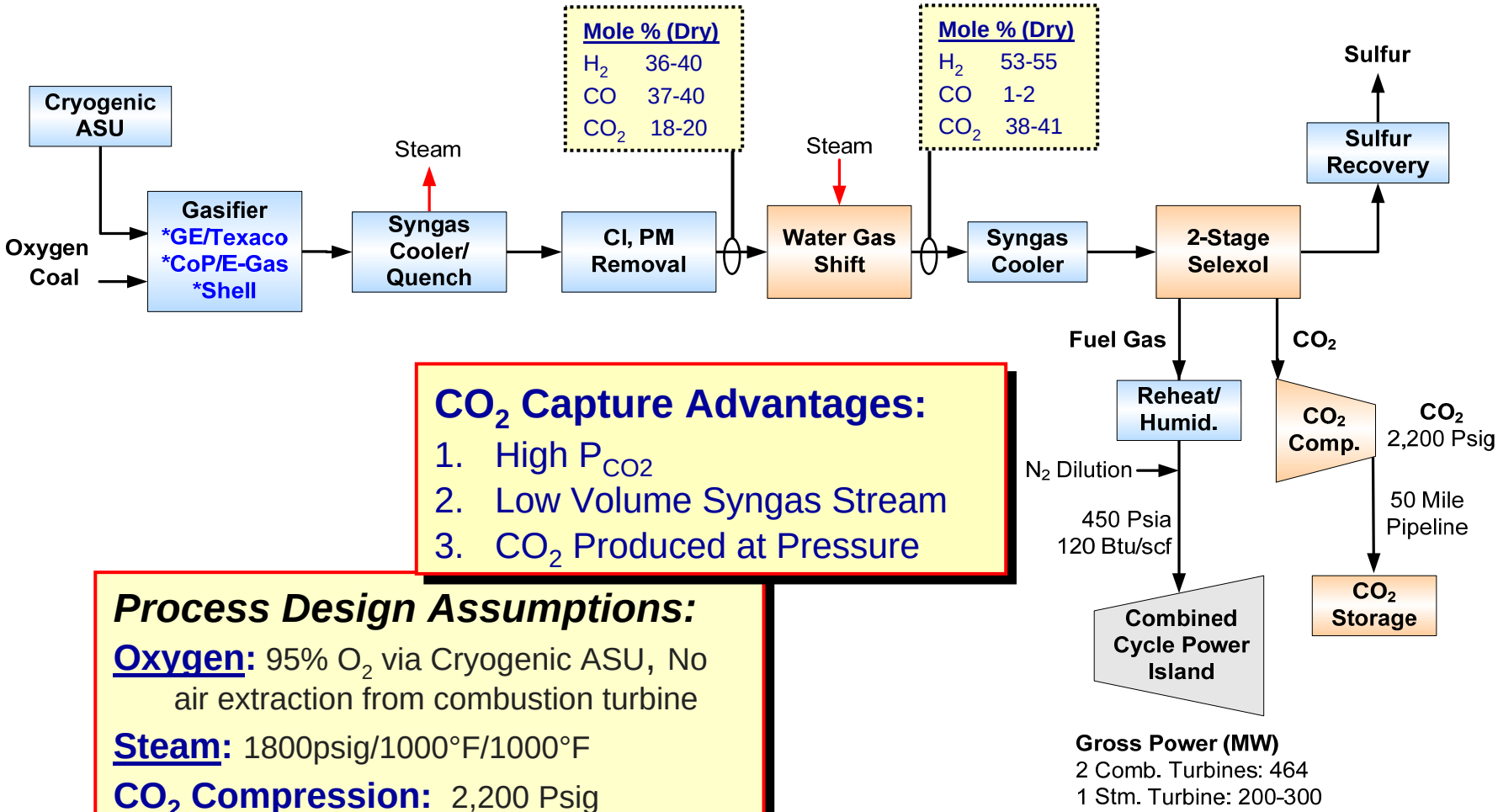
Oxygen: 95% O_2 via Cryogenic ASU, ~4-7% Air Extraction from combustion turbine

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

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 Design Assumptions:

Oxygen: 95% O_2 via Cryogenic ASU, No air extraction from combustion turbine

Steam: 1800psig/1000°F/1000°F

CO_2 Compression: 2,200 Psig

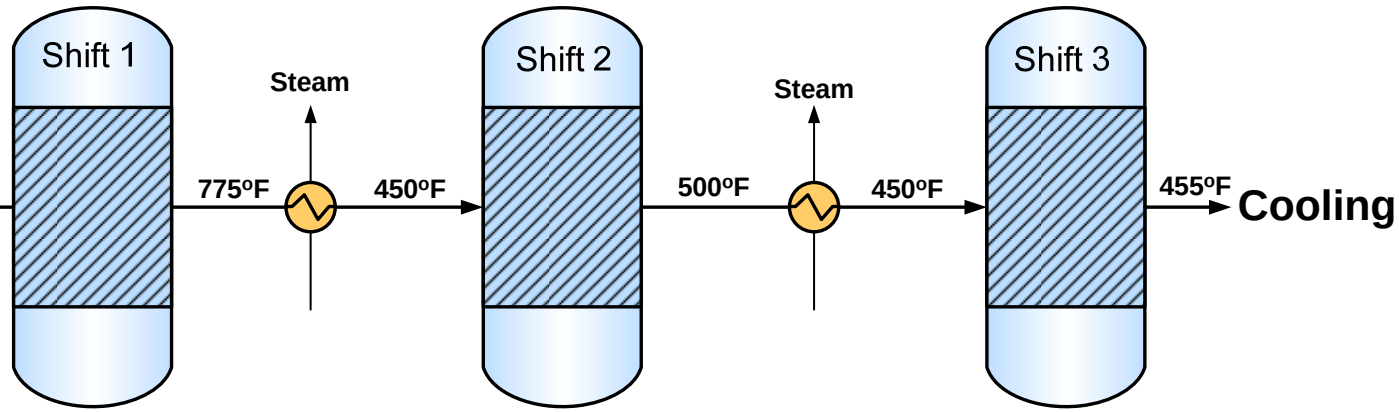
Water-Gas Shift Reactor System

Design:

- Haldor Topsoe SSK Sulfur Tolerant Catalyst
- Up to 97.5% CO Conversion
- 2 stages for GE and Shell, 3 stages for E-Gas
- H_2O/CO = 2.0 (Project Assumption)
- Overall ΔP = ~30 psia

H_2O/CO Ratio[1]	
GE	1.3
E-Gas	0.4
Shell	1.5

[1] Prior to shift steam addition



	Relative HP* Steam Flow	Steam Turbine Output (MW)
GE	1.0	275
E-Gas	2.4	230
Shell	0.9	230

*High Pressure Steam

$$H_2O + CO \longleftrightarrow CO_2 + H_2$$

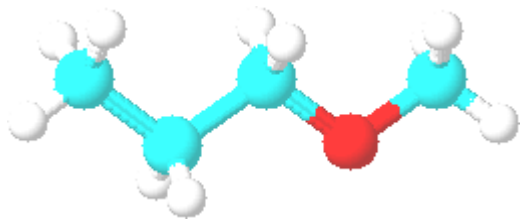
CO_2 Capture via Selexol Scrubbing

Advantages

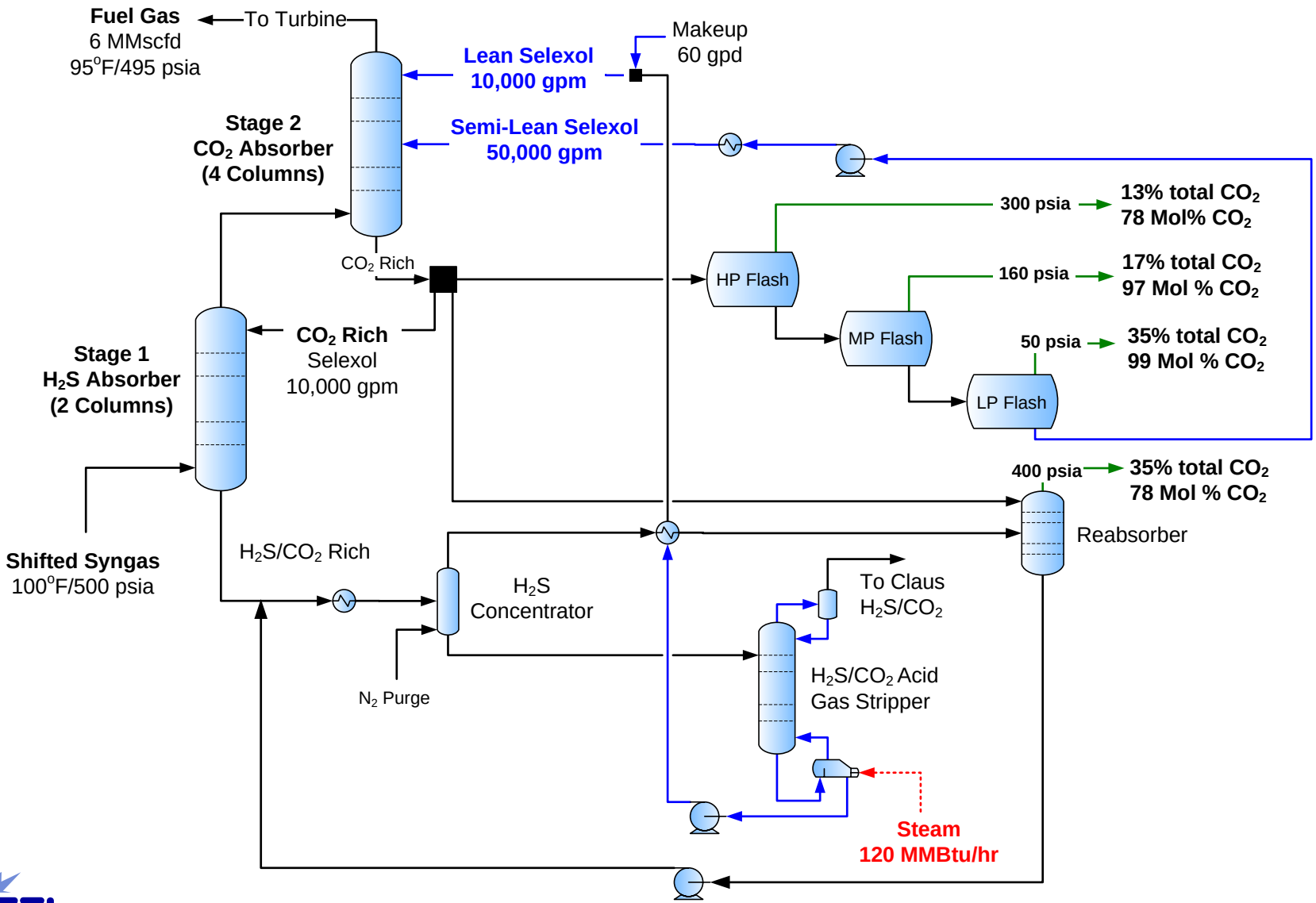
- Physical Liquid Sorbent → High loadings at high CO_2 partial pressure
- Highly selective for H_2S and CO_2 → No need for separate sulfur capture system
- No heat of reaction (ΔH_{rxn}), small heat of solution
- Chemically and thermally stable, low vapor pressure
- 30+ years of commercial operation (55 worldwide plants)

Disadvantages

- Requires Gas Cooling (to ~100°F)
- CO_2 regeneration by flashing



Selexol™ Scrubbing



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] $\underline{CO_2 \text{ Capture Energy Penalty}}$ = Percent points decrease in net power plant efficiency due to CO_2 Capture

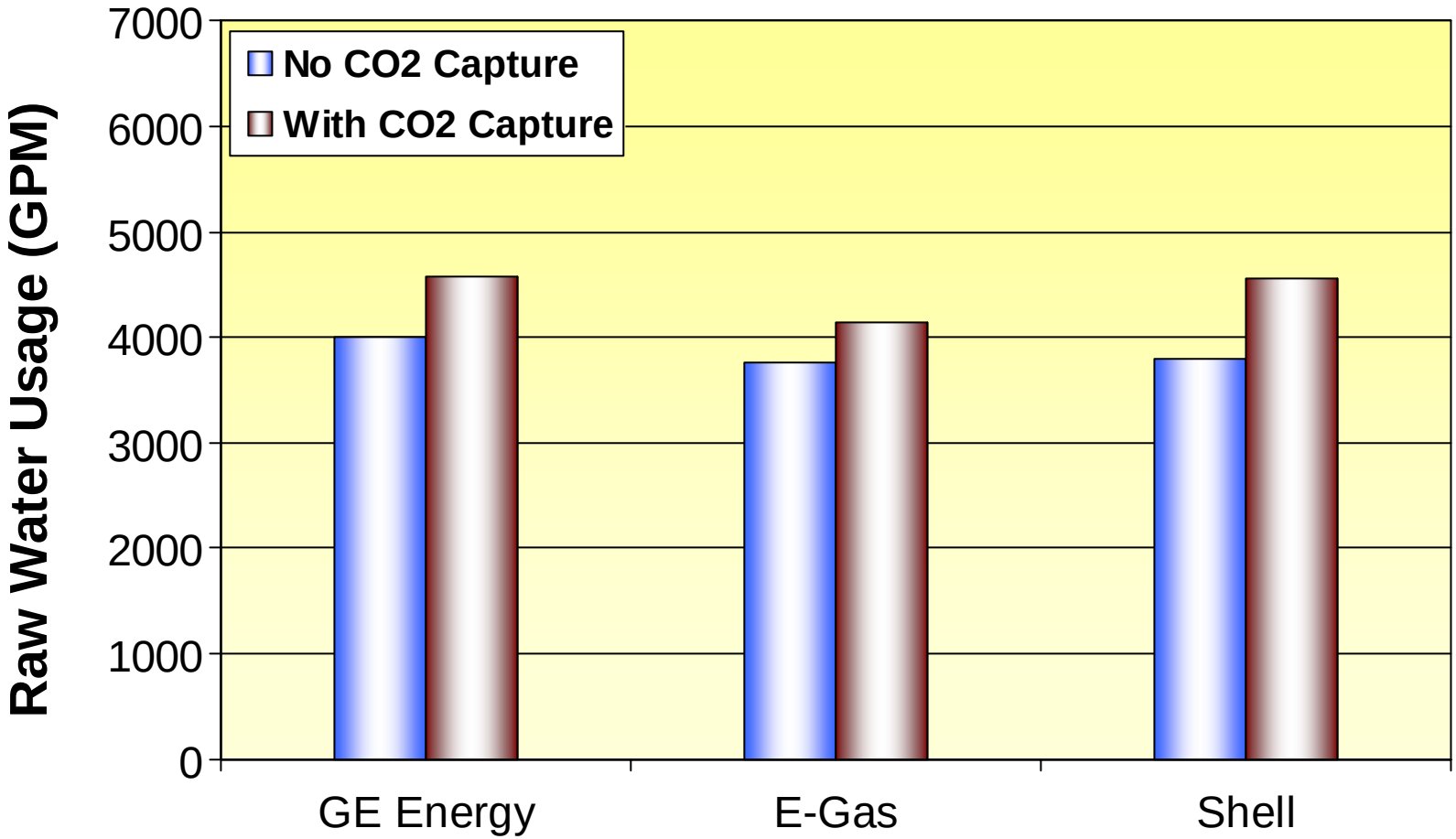
IGCC Performance Summary

	GE Energy		E-Gas		Shell	
CO_2 Capture	NO	YES	NO	YES	NO	YES
Gross Power (MW)	**770**	**745**	**743**	**694**	**748**	**694**
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
Heat Rate (Btu/kWh)	8,922	10,505	8,681	10,757	8,304	10,674
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 ~6-9 percentage points

Water Usage in IGCC Plants



IGCC Economic Results

Total Plant Cost

	GE Energy		E-Gas		Shell	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Plant Cost ($/kWe)[1]						
Base Plant	1,323	1,566	1,272	1,592	1,522	1,817
Air Separation Unit	287	342	264	329	256	336
Gas Cleanup/CO_2 Capture	203	414	197	441	199	445
CO_2 Compression	-	68	-	69	-	70
Total Plant Cost ($/kWe)	**1,813**	**2,390**	**1,733**	**2,431**	**1,977**	**2,668**
Increase in TPC ($/kWe)	-	577	-	698	-	691

IGCC Economic Results

Cost of Electricity

	GE Energy		E-Gas		Shell	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
Total Plant Cost ($/kWe)	**1,813**	**2,390**	**1,733**	**2,431**	**1,977**	**2,668**
Plant Capital COE (¢/kWh)	4.53	5.97	4.33	6.07	4.94	6.66
Plant O&M COE (¢/kWh)	3.27	3.93	3.20	4.09	3.11	3.97
Total Plant COE (¢/kWh)	7.80	9.90	7.53	10.16	8.05	10.63
CO_2 TS&M COE (¢/kWh)	-	0.39	-	0.41	-	0.41
Total COE[2] (¢/kWh)	**7.80**	**10.29**	**7.53**	**10.57**	**8.05**	**11.04**
Increase in COE (¢/kWh)	**-**	**2.49**	**-**	**3.04**	**-**	**2.99**
Increase in COE (%)	**-**	**32**	**-**	**40**	**-**	**37**
$/ton CO_2 Avoided	-	32	-	41	-	42

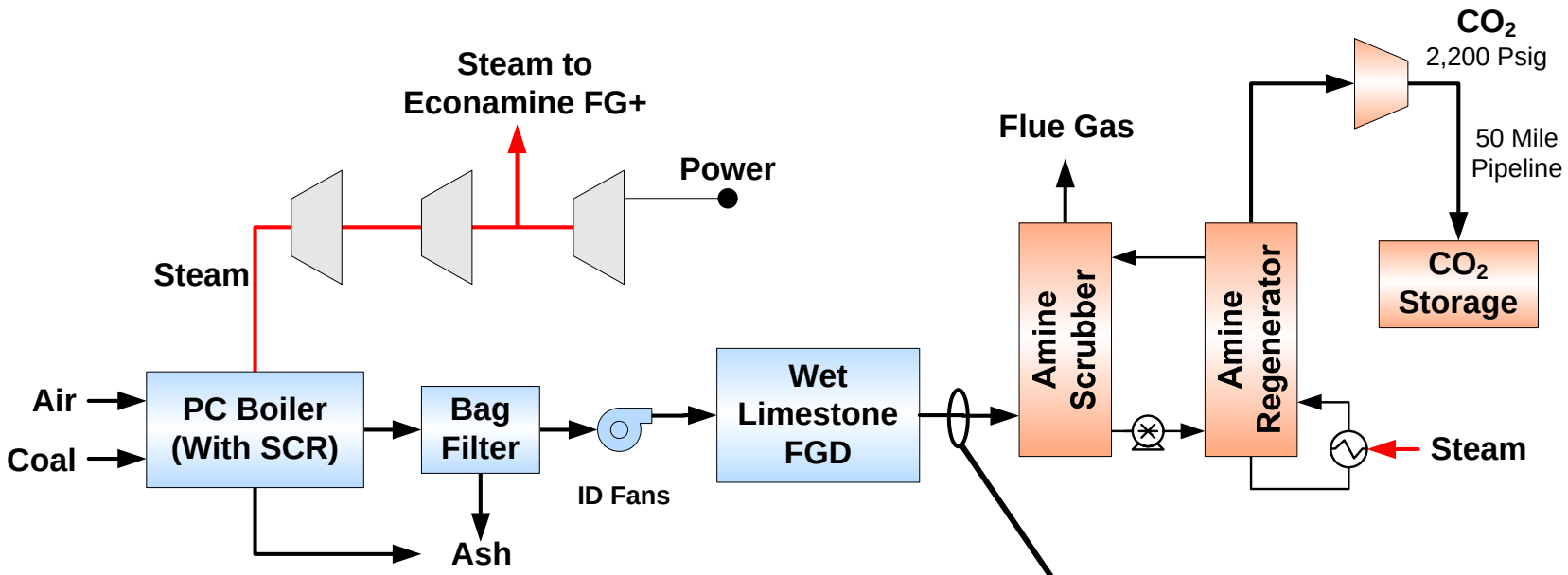
CO_2 transport, storage and monitoring adds <0.5 ¢/kWh
Increase in COE ~ 3 cents/kWh (~ ↑36%)

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)

Amine Scrubbing Advantages/Disadvantages

Amine Advantages

1. **Proven Technology → Remove CO_2 and H_2S from NG**
2. **Chemical solvent → *High* loadings at *low* CO_2 partial pressure**
3. **Relatively Cheap ($1.50-2.0 per lb chemical)**

Amine Disadvantages

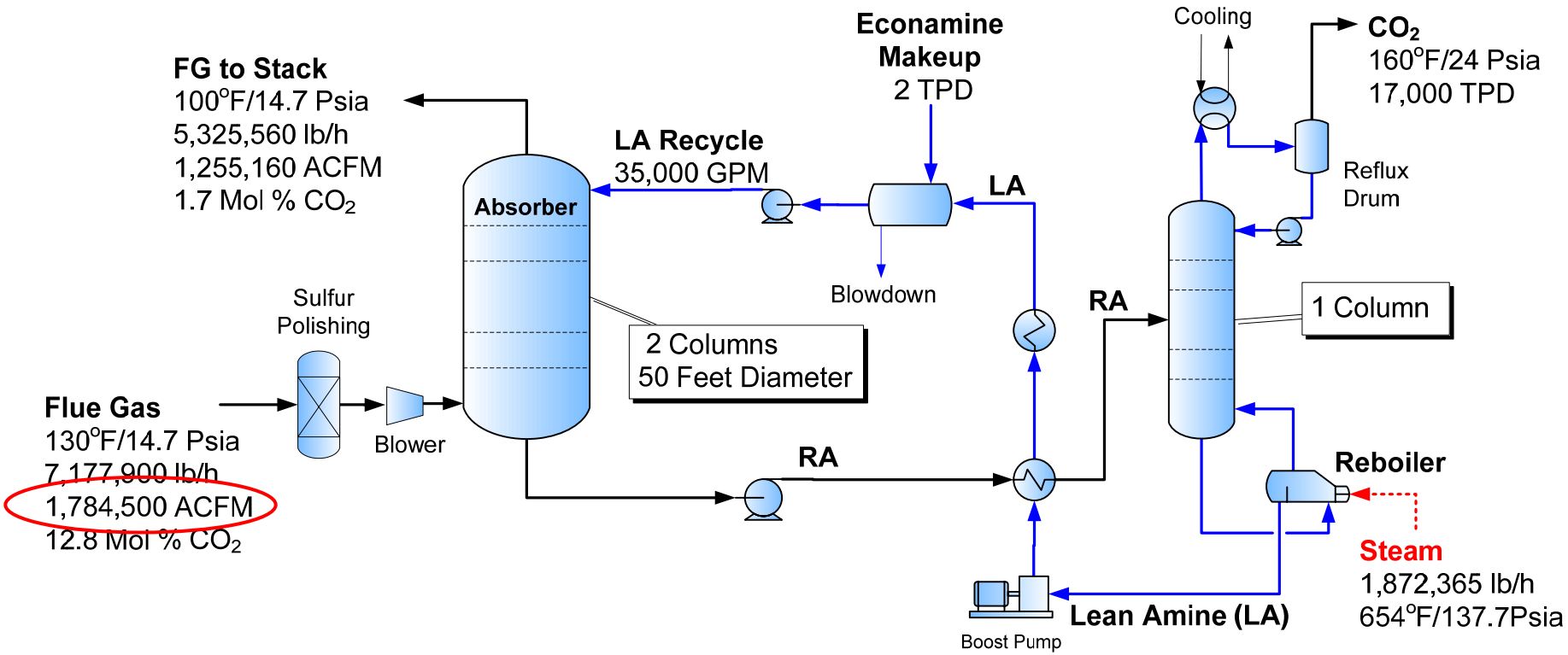
1. **High heat of reaction → high regeneration energy required**
   - 1,500 to 3,500 Btu/lb CO_2 removed
   - Low pressure steam derates power plant by 20 to 40%
2. **Degradation and Corrosion**
   - Requires < 10ppm sulfur
3. **High cost**

Amine Scrubbing Improvements

Amine CO_2 scrubbing technology leaders are Fluor (Econamine FG Plus^{SM}) and Mitsubishi Heavy Industry

Improvements	Benefits	Outcome
1. New Solvent Formulation	↑ Reaction Rates	↓ Packing volume, ↓ Absorber size ↓ Absorber cost
	↑ CO_2 Capacity	↓ Solvent circulation, ↓ Reboiler Duty
2. Heat Integration	↑ Reaction Rates	↓ Packing volume, ↓ Absorber size ↓ Absorber cost
	↑ CO_2 Capacity	↓ Solvent circulation, ↓ Reboiler Duty
3. Split Flow	↓ Reboiler Duty	↑ Power plant efficiency
4. Condensate Flash Steam Stripping	↓ Semi-Lean Loading	↓ Reboiler Duty
5. Integrated Steam Generation	↓ Reboiler Duty	↑ Power plant efficiency
6. Larger Diameter Vessels	60 foot diameter	Accommodate power plants
7. Non-Thermal Reclaimer	↓ Solvent Losses	↓ Solvent make-up costs, eliminate any solid hazardous waste

Fluor Econamine FG Plus^{SM} Scrubbing



Reboiler Heat Duty (Btu/lb CO_2)	1,550	Regeneration (°F)	250's
MEA Circulation Rate (GPM)	35,000	Auxiliary Power (MW)	21-24
Absorption (°F)	100's	Induced Draft Fan (MW)	13-15

Subcritical PC Performance

	Subcritical	
Coal Flow Rate (Ton/day)	**5,252**	**7,759**
CO_2 Captured (Ton/day)	**0**	**16,566**
Gross Power (MW)	**583**	**680**
Auxiliary Power (MW)		
Base Plant Load	21	35
Forced + Induced Draft Fans	9	14
Flue Gas Cleanup	3	5
CO_2 Capture	-	24
CO_2 Compression	-	52
Total Aux. Power (MW)	**33**	**130**
Net Power (MW)	**550**	**550**
Efficiency (%HHV)	**36.8**	**24.9**
Energy Penalty (% Points)	**-**	**11.9**

48% Increase in Coal Feed Rate

Larger Base Plant

MEA Scrubbing

~17,000 TPD to 2,200 Psig

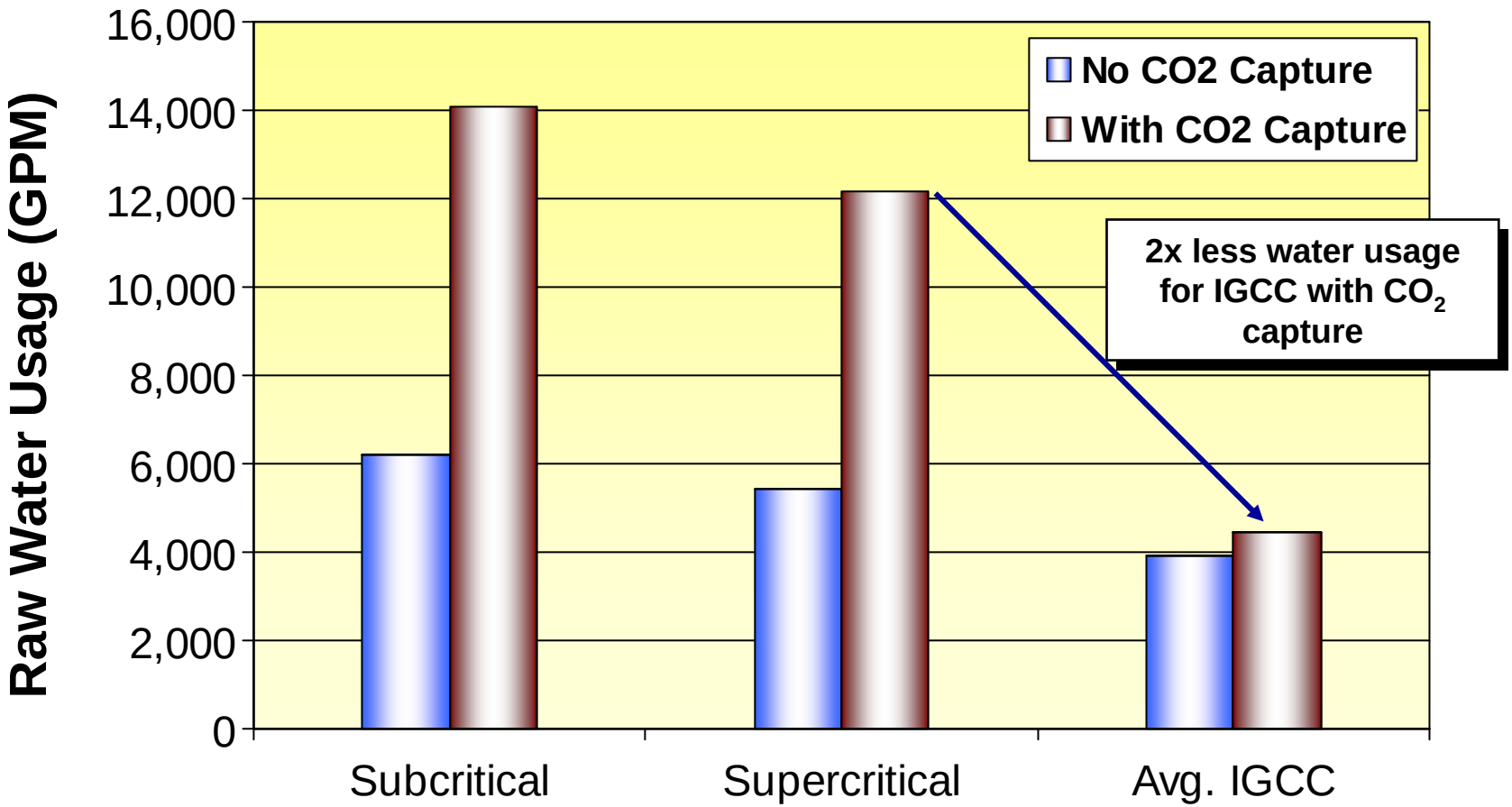
CO_2 Capture decreases net efficiency by ~12 percentage points

Pulverized Coal Performance Summary

	Subcritical		Supercritical	
Coal Flow Rate (Ton/day)	**5,252**	**7,759**	**4,935**	**7,039**
CO_2 Captured (Ton/day)	**0**	**16,566**	**0**	**15,029**
Gross Power (MW)	**583**	**680**	**580**	**663**
Auxiliary Power (MW)				
Base Plant Load	21	35	18	32
Forced + Induced Draft Fans	9	14	9	13
Flue Gas Cleanup	3	5	3	4
CO_2 Capture	-	24	-	21
CO_2 Compression	-	52	-	47
Total Aux. Power (MW)	**33**	**130**	**30**	**117**
Net Power (MW)	**550**	**550**	**550**	**546**
Efficiency (%HHV)	**36.8**	**24.9**	**39.1**	**27.2**
Energy Penalty (% Points)	**-**	**11.9**	**-**	**11.9**

CO_2 Capture decreases net efficiency by ~12 percentage points

Water Usage in PC and IGCC Plants



Pulverized Coal Economic Results Summary

Total Plant Cost

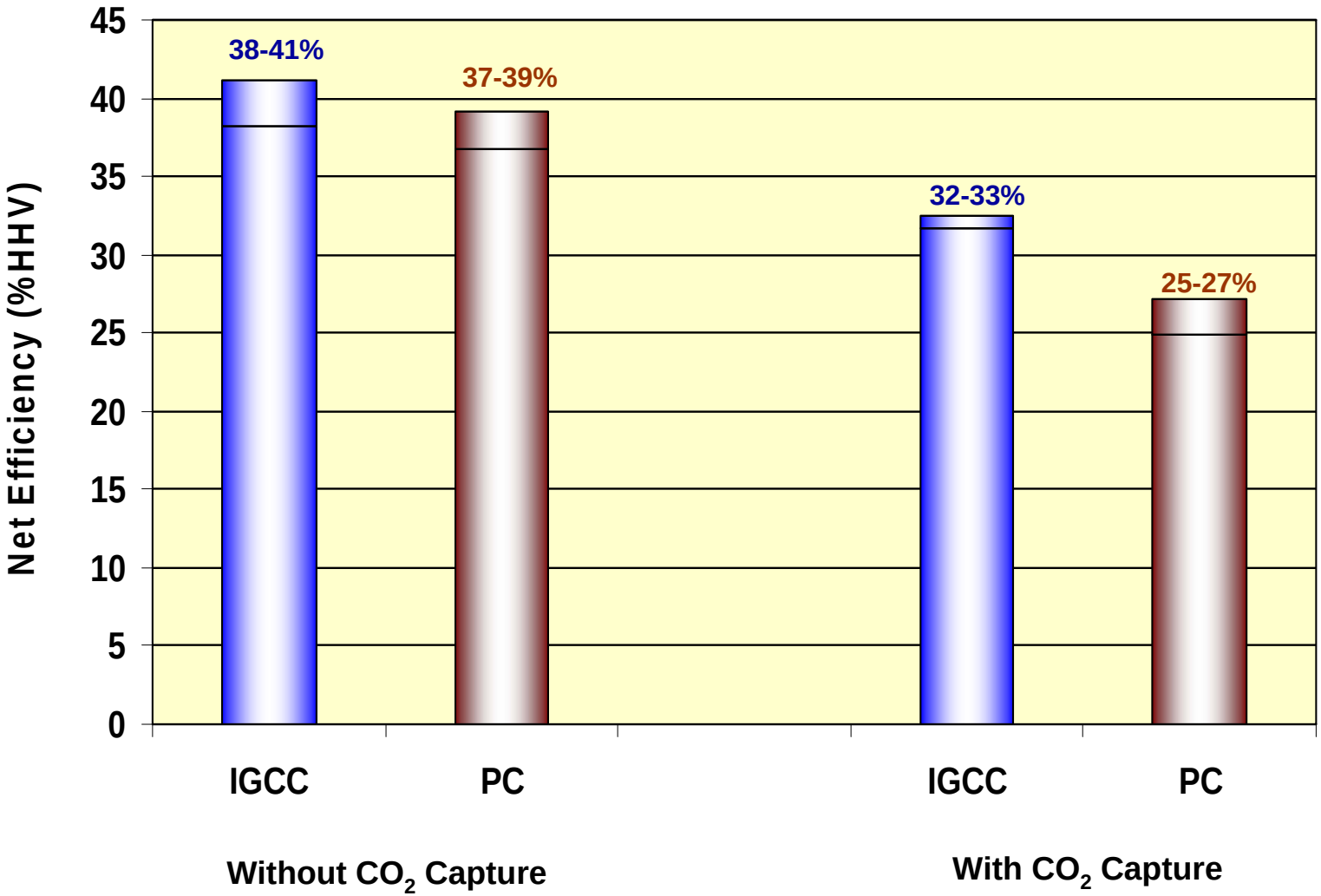
	Subcritical		Supercritical	
CO_2 Capture	NO	YES	NO	YES
Plant Cost ($/kWe)				
Base Plant	1,303	1,691	1,346	1,731
SOx and NOx Cleanup	246	323	229	302
CO_2 Capture	-	792	-	752
CO_2 Compression	-	89	-	85
Total Plant Cost ($/kWe)	**1,549**	**2,895**	**1,575**	**2,870**
Increase in TPC ($/kWh)	-	1,346	-	1,295

Pulverized Coal Economic Results Summary

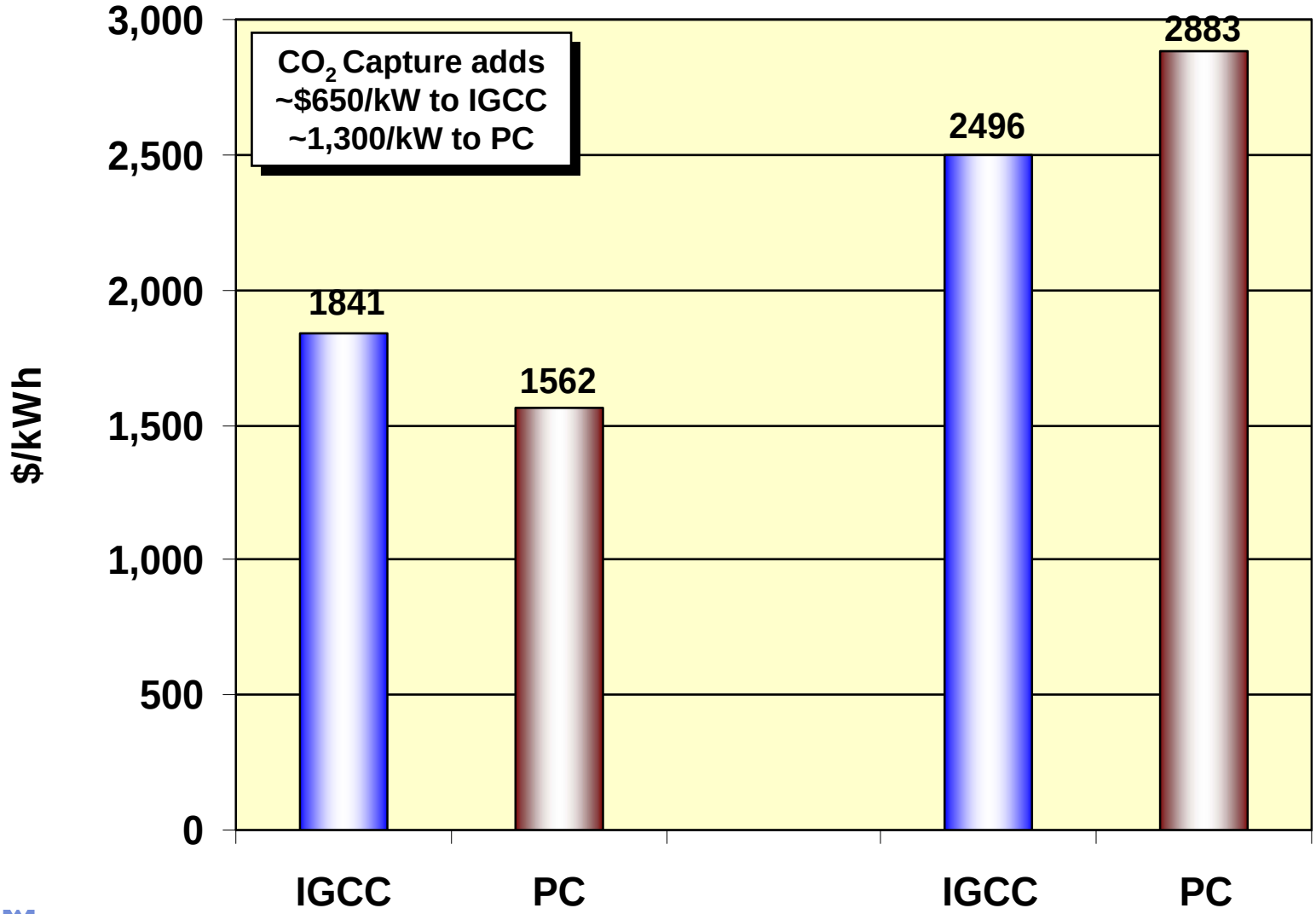
	Subcritical		Supercritical	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**
Total Plant Cost ($/kWe)	**1,549**	**2,895**	**1,575**	**2,870**
Plant Capital COE (¢/kWh)	3.41	6.81	3.47	6.75
Plant O&M COE (¢/kWh)	2.99	4.64	2.86	4.34
Total Plant COE (¢/kWh)	6.40	11.45	6.33	11.09
CO_2 TS&M COE (¢/kWh)	0.00	0.43	0.00	0.39
Total COE (¢/kWh)	**6.40**	**11.88**	**6.33**	**11.48**
Increase in COE (¢/kWh %)	**-**	**5.48**	**-**	**5.15**
Increase in COE (%)	**-**	**86**	**-**	**81**
$/ton CO_2 Avoided		**68**		**68**

CO_2 transport, storage and monitoring adds <0.5 ¢/kWh
Increase in COE ~ 5 cents/kWh (~ ↑84%)

Net Efficiency Comparison

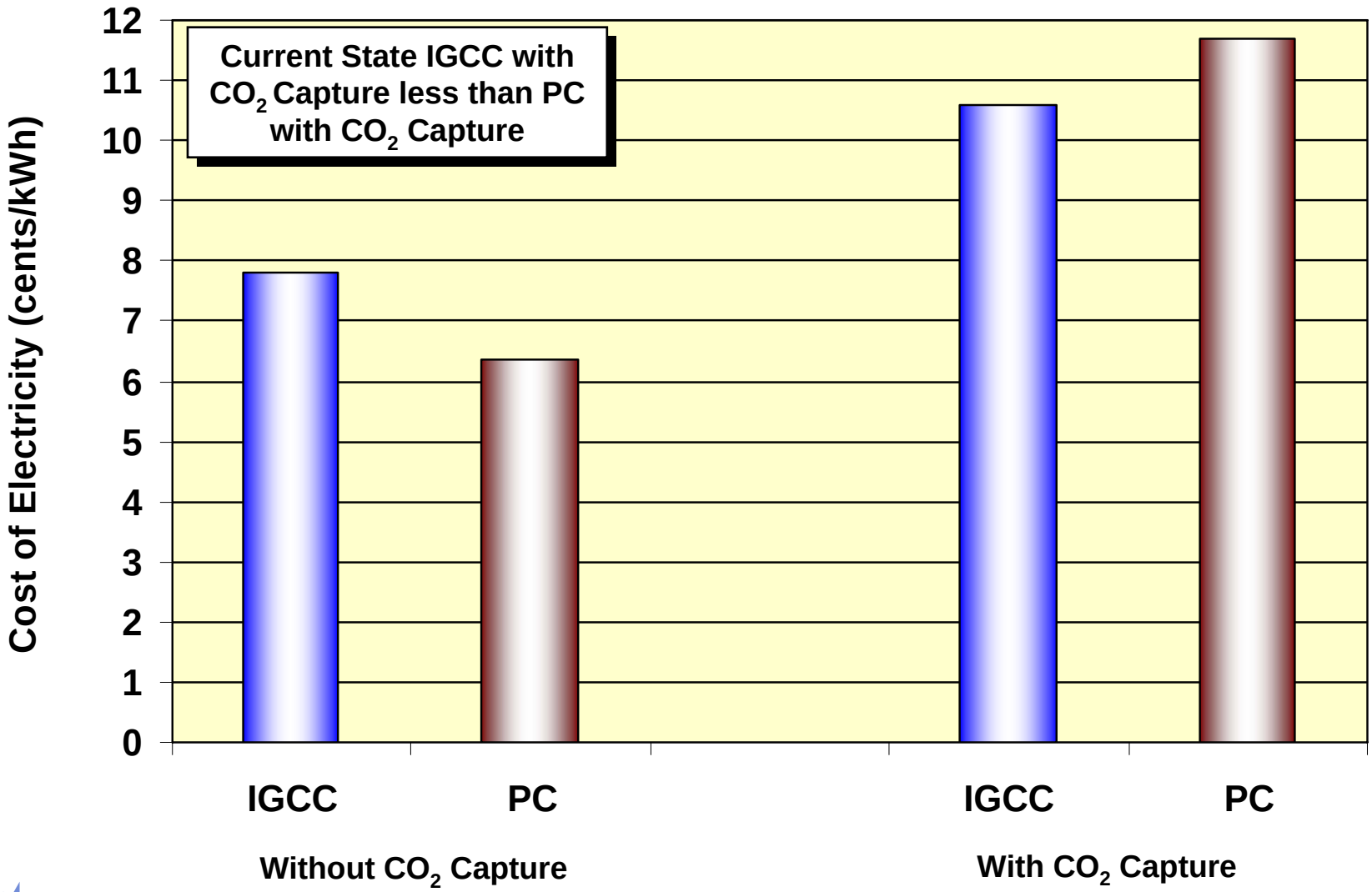


Average Total Plant Cost Comparison



Total Plant Capital Cost includes contingencies and engineering fees

Average Cost of Electricity Comparison



NETL Viewpoint

- **Establishes baseline performance and cost estimates for current state of technology**

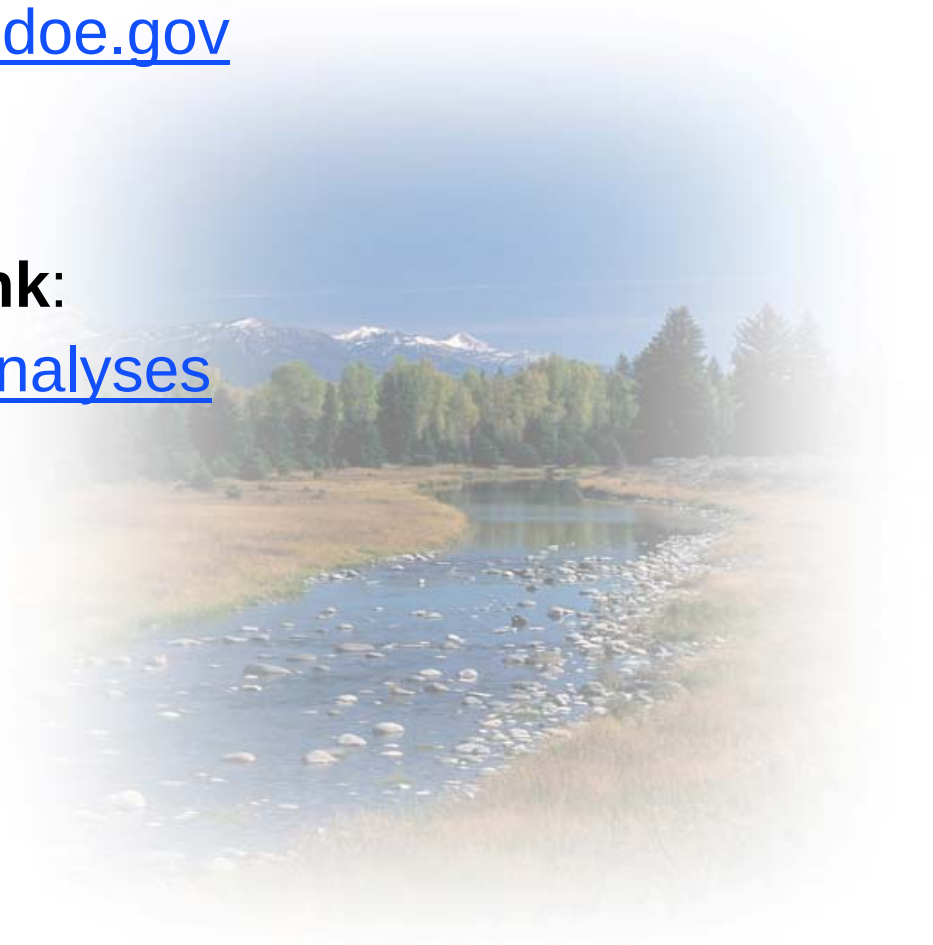
- **Improved efficiencies and reduced costs are required to improve competitiveness of advanced coal-based systems**
  - In today's market and regulatory environment
  - Also in a carbon constrained scenario

- **Fossil Energy RD&D aimed at improving performance and cost of clean coal power systems including development of new approaches to capture and sequester greenhouse gases**

Thank You!

Email: Jared.Ciferno@netl.doe.gov
Phone: 412-386-5862

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



Supplemental Slides

Contracting Approach

- **EPCM vs. EPC**
  - EPCM (engineering, procurement, construction management)
    - Owner has control of project
    - Risk is reduced with time as scope definition improves by time of contract award
  - EPC (engineer, procure, construct)
    - Lump sum contract where contractor assumes all risk for performance, schedule, and cost
    - If willing to accept risk, premiums applied can raise costs dramatically
- **This study assumes EPCM so costs do not include "risk wrap"**

Pulverized Coal Economic Results Summary

	Subcritical		Supercritical	
CO_2 Capture	NO	YES	NO	YES
Plant Cost ($/kWe)				
Base Plant	1,303	1,691	1,346	1,731
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CO_2 Compression	-	89	-	85
Total Plant Cost ($/kWe)	1,549	2,895	1,575	2,870
Capital COE (¢/kWh)	3.41	6.81	3.47	6.75
O&M COE (¢/kWh)	2.99	4.64	2.86	4.34
CO_2 TS&M COE (¢/kWh)	0.00	0.43	0.00	0.39
Total LCOE (¢/kWh)	6.40	11.88	6.33	11.48
Increase in COE (%)	-	86	-	81
$/ton CO_2 Avoided		68		68

IGCC Economic Results

	GE Energy		E-Gas		Shell	
CO_2 Capture	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**
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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	3.93	3.20	4.09	3.11	3.97
CO_2 TS&M COE (¢/kWh)	0.00	0.39	0.00	0.41	0.00	0.41
Total COE[2] (¢/kWh)	**7.80**	**10.29**	**7.53**	**10.57**	**8.05**	**11.04**
Increase in COE (%)	**-**	**32**	**-**	**40**	**-**	**37**
$/tonne CO_2 Avoided	-	35	-	45	-	46

[1]Total Plant Capital Cost (Includes contingencies and engineering fees)

[2]January 2007 Dollars, 80% Capacity Factor, 17.5% Capital Charge Factor, Coal cost $1.80/$10^6$Btu