# Fifth Annual Conference on Carbon Capture & Sequestration

***Steps Toward Deployment***

*CCS Economic Analyses*

## 2006 Cost & Performance Comparison of Fossil Energy Power Plants

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NETL

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# Overview

- **<u>Purpose</u>: To compare near-term commercial offerings for IGCC, PC and NGCC cases both with and without current technology for $CO_2$ capture**
  - Developed with consistent design requirements and up-to-date performance and capital cost estimates
  - Considered technologies that could be built now and deployed by 2010
  - Provides baseline costs and performance for which to compare advancing technologies within the FE R&D Program
- **Public report available Summer 2006**

# Study Matrix

| Case | Plant Type | ST Cond. (psig/°F/°F) | GT | Gasifier/ Boiler | Acid Gas Removal / $CO_2$ Separation / Sulfur Recovery | $CO_2$ Cap |
|---|---|---|---|---|---|---|
| 1 | IGCC | 1800/1050/1050 | F Class | GE | Selexol / - / Claus | |
| 2 | | | | | Selexol / Selexol / Claus | 90% |
| 3 | | | | CoP E-Gas | MDEA / - / Claus | |
| 4 | | | | | Selexol / Selexol / Claus | 90% |
| 5 | | | | Shell | Sulfinol-M / - / Claus | |
| 6 | | | | | Selexol / Selexol / Claus | 90% |
| 7 | PC | 2400/1050/1050 | | Subcritical | Wet FGD / - / Gypsum | |
| 8 | | | | | Wet FGD / Econamine / Gypsum | 90% |
| 9 | | 3500/1100/1100 | | Supercritical | Wet FGD / - / Gypsum | |
| 10 | | | | | Wet FGD / Econamine / Gypsum | 90% |
| 11 | NGCC | 2400/1050/950 | F Class | HRSG | | |
| 12 | | | | | - / Econamine / - | 90% |

GEE – GE Energy
CoP – Conoco Phillips

# Design Basis: 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 |

# Design Basis: Assumptions

## *Economic*

| | |
|---|---|
| **Startup** | **2010** |
| **Plant Life (Years)** | **20** |
| **Capital Charge Factor (%)** | **13.8** |
| **Dollars (Constant)** | **2006** |
| **Coal ($/MM Btu)** | **1.34** |
| **Capacity Factor** | **85** |

## *Site*

**Greenfield, Midwestern USA, 0 ft Elevation**

**Rail and Highway Access**

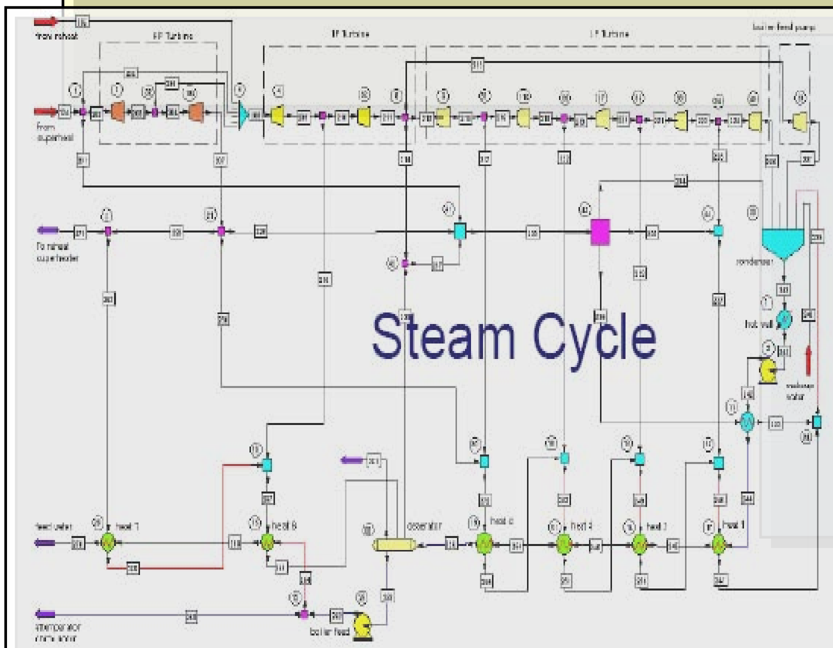
**Municipal Water**

**300 Acres**

# 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**

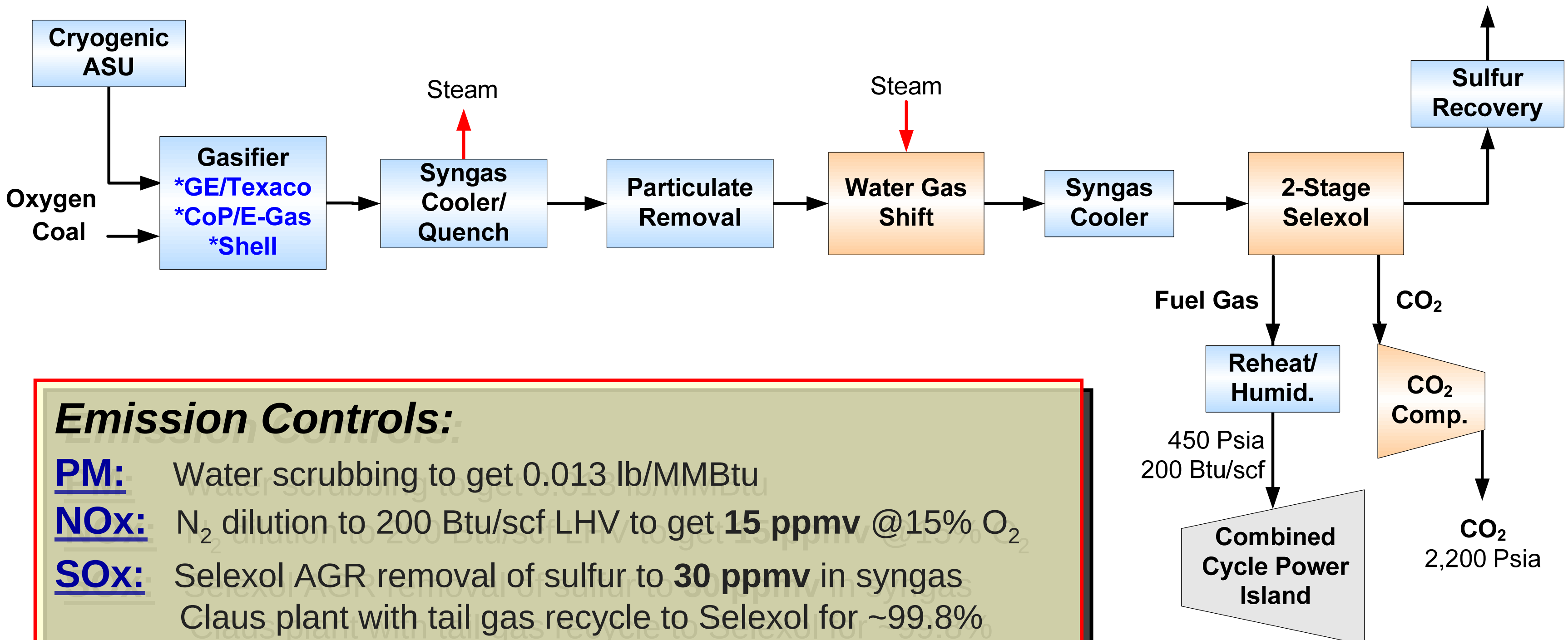
# IGCC Power Plant

# *Current State* $CO_2$ Capture Using Selexol™

Pre-Combustion $CO_2$ Capture Baseline

# Pre-Combustion Current Technology

## *IGCC Power Plant with $CO_2$ Scrubbing*




***Emission Controls:***

**PM:** Water scrubbing to get 0.013 lb/MMBtu

**NOx:** $N_2$ dilution to 200 Btu/scf LHV to get **15 ppmv** @15% $O_2$

**SOx:** Selexol AGR removal of sulfur to **30 ppmv** in syngas
Claus plant with tail gas recycle to Selexol for ~99.8% overall S recovery

**Hg:** Activated Carbon beds for ~90% removal

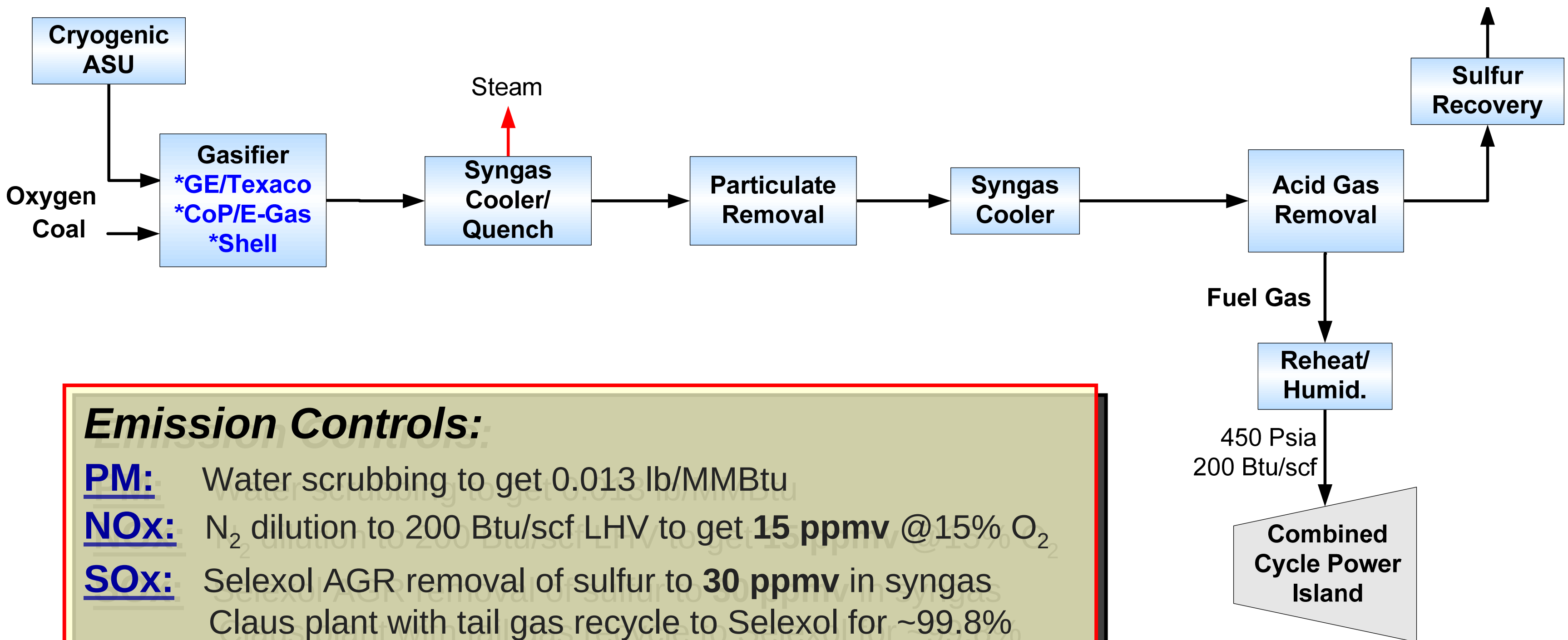
**Advanced F-Class Turbine - 232 MWe (42% LHV)**

**Steam Conditions - 1800 psig/1050°F/1050°F**

**Gross Power (MW)**
2 Comb. Turbines: 464
1 Stm. Turb: 200-300
**Total Gross: 664-764**

# IGCC Current Technology

## *IGCC Power Plant without $CO_2$ Capture*




***Emission Controls:***

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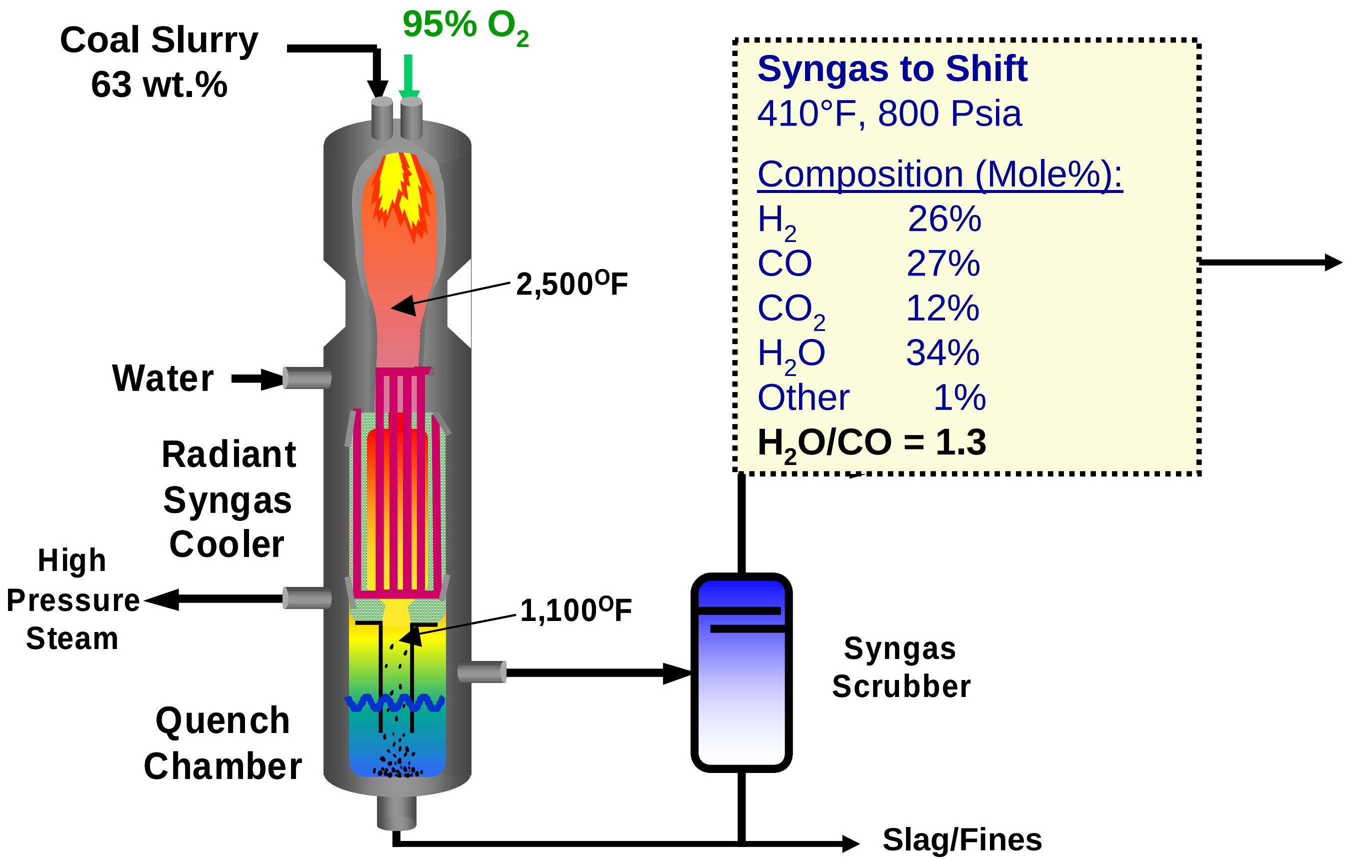
**Gross Power (MW)**
2 Comb. Turbines: 464
1 Stm. Turb: 200-300
**Total Gross: 664-764**

# Cases 1 & 2:  GE Energy Radiant




**Syngas to Shift**
410°F, 800 Psia

Composition (Mole%):

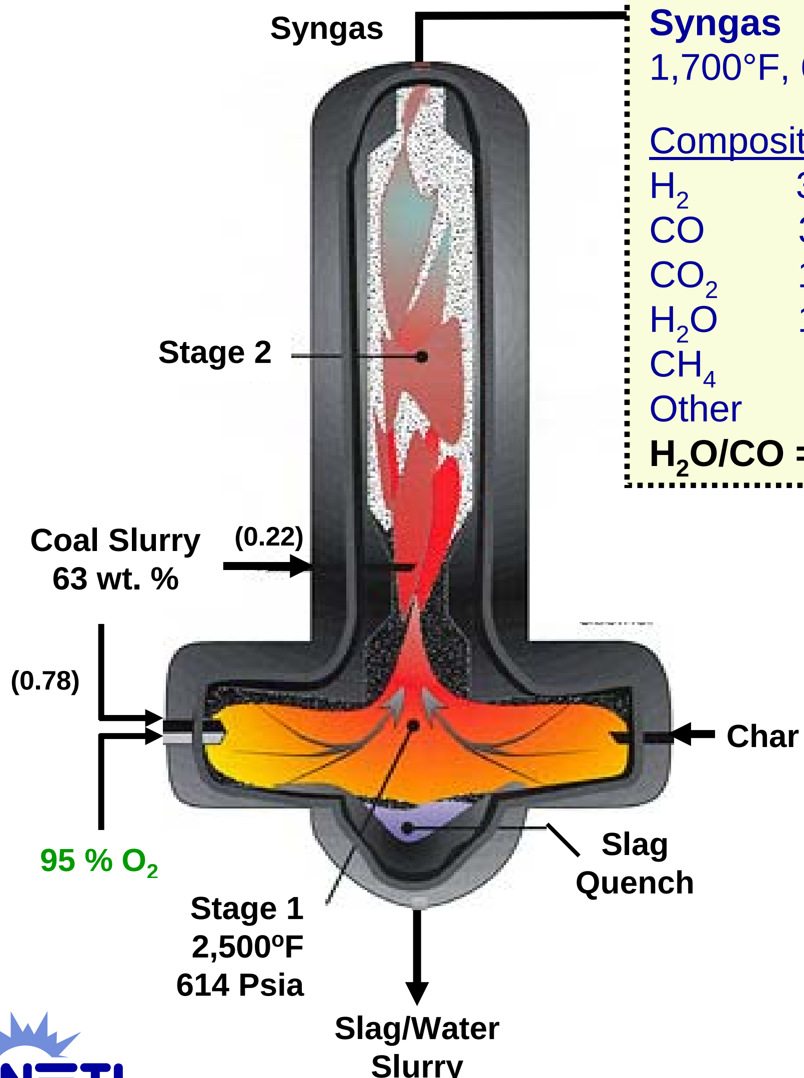
| | |
|---|---|
| $H_2$ | 26% |
| CO | 27% |
| $CO_2$ | 12% |
| $H_2O$ | 34% |
| Other | 1% |

**$H_2O$/CO = 1.3**

**Design**:  Pressurized, single-stage, downward firing, entrained flow, slurry feed, oxygen blown, slagging, radiant and quench cooling

**Note**:  All gasification performance data estimated by the project team to be representative of GE gasifier

# Cases 3 & 4: ConocoPhillips E-Gas™




**Syngas**
1,700°F, 614 psia

Composition (Mole%):

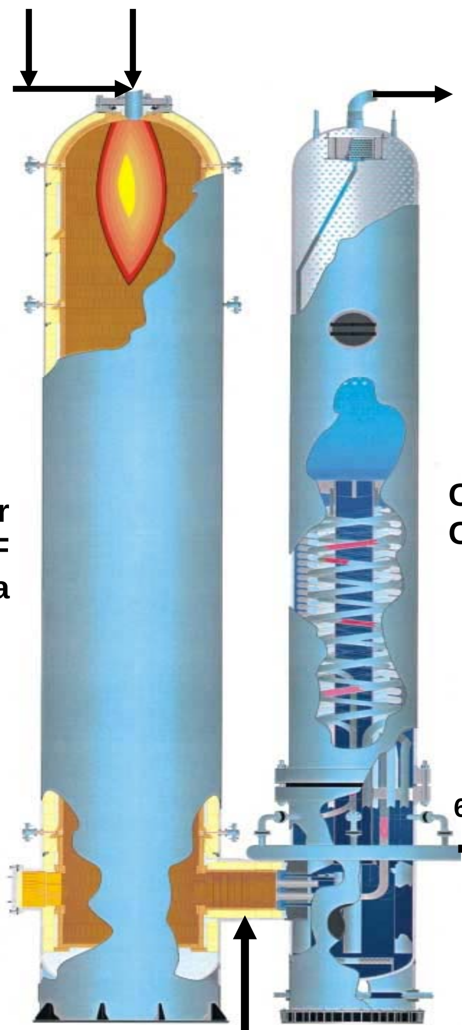
| | |
|---|---|
| $H_2$ | 30% |
| CO | 31% |
| $CO_2$ | 17% |
| $H_2O$ | 16% |
| $CH_4$ | 3% |
| Other | 3% |

**$H_2O/CO = 0.4$**

**Design**: Pressurized, two-stage, upward firing, entrained flow, slurry feed, oxygen blown, slagging, fire-tube boiler syngas cooling, syngas recycle

**Note**: All gasification performance data estimated by the project team to be representative of an E-Gas gasifier

# Cases 5 & 6: Shell Gasification




**Soot Quench & Scrubber** → **Syngas** → **To Shift**

**Design**: Pressurized, single-stage, downward firing, entrained flow, dry feed, oxygen blown, convective cooler

**Note**: All gasification performance data estimated by the project team to be representative of Shell gasifier

**Syngas**
350°F, 600 Psia

Composition (Mole%):

| | |
|---|---|
| $H_2$ | 29% |
| CO | 60% |
| $CO_2$ | 2% |
| $H_2O$ | 4% |
| Other | 5% |

**$H_2O/CO$ = 0.1**

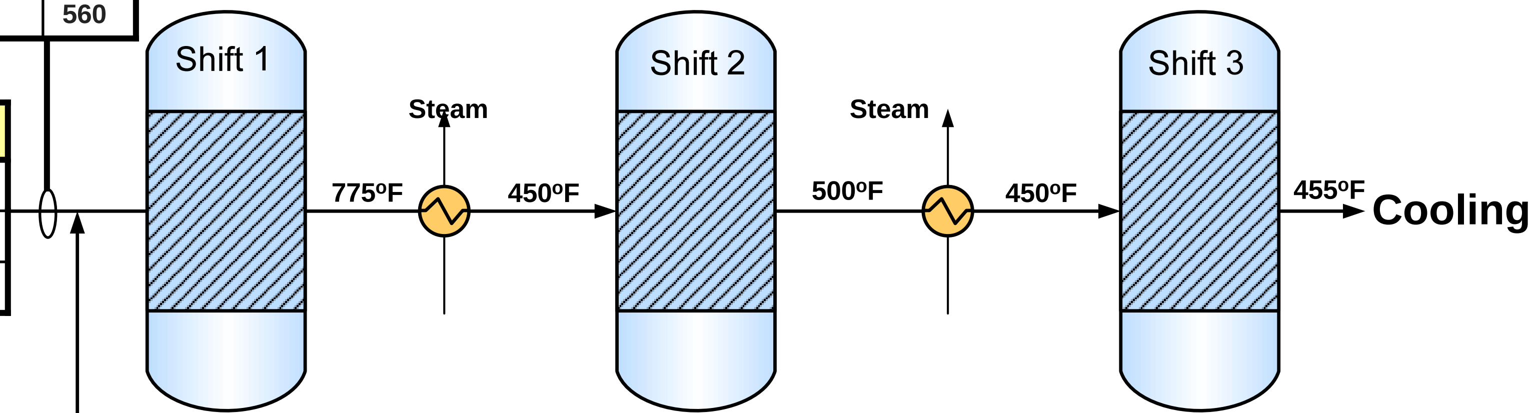
Source: "The Shell Gasification Process", Uhde, ThyssenKrupp Technologies

# Water-Gas Shift Reactor System

**Design**:
- Haldor Topsoe SSK Sulfur Tolerant Catalyst
- Up to 99% CO Conversion
- $H_2O/CO$ = 2.3 (Project Assumption)
- Overall $\Delta P$ = ~30 psia

| Pressure (Psia) | |
|---|---|
| GE | 800 |
| E-Gas | 560 |
| Shell | 560 |

| $H_2O/CO$ Ratio | |
|---|---|
| GE | 1.3 |
| E-Gas | 0.4 |
| Shell | 0.1 |




| | Relative HP* Steam Flow | Steam Turbine Output (MW) |
|---|---|---|
| GE | 1.0 | 270 |
| E-Gas | 2.0 | 216 |
| Shell | 2.8 | 202 |

*High Pressure Steam

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

***$H_2O/CO$ has great effect on relative performance***

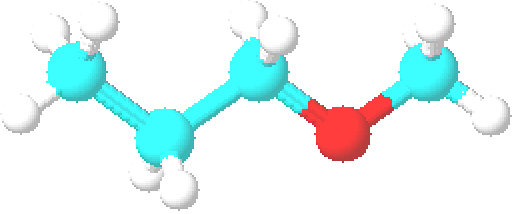
# $CO_2$ Capture via Selexol Scrubbing

## Advantages

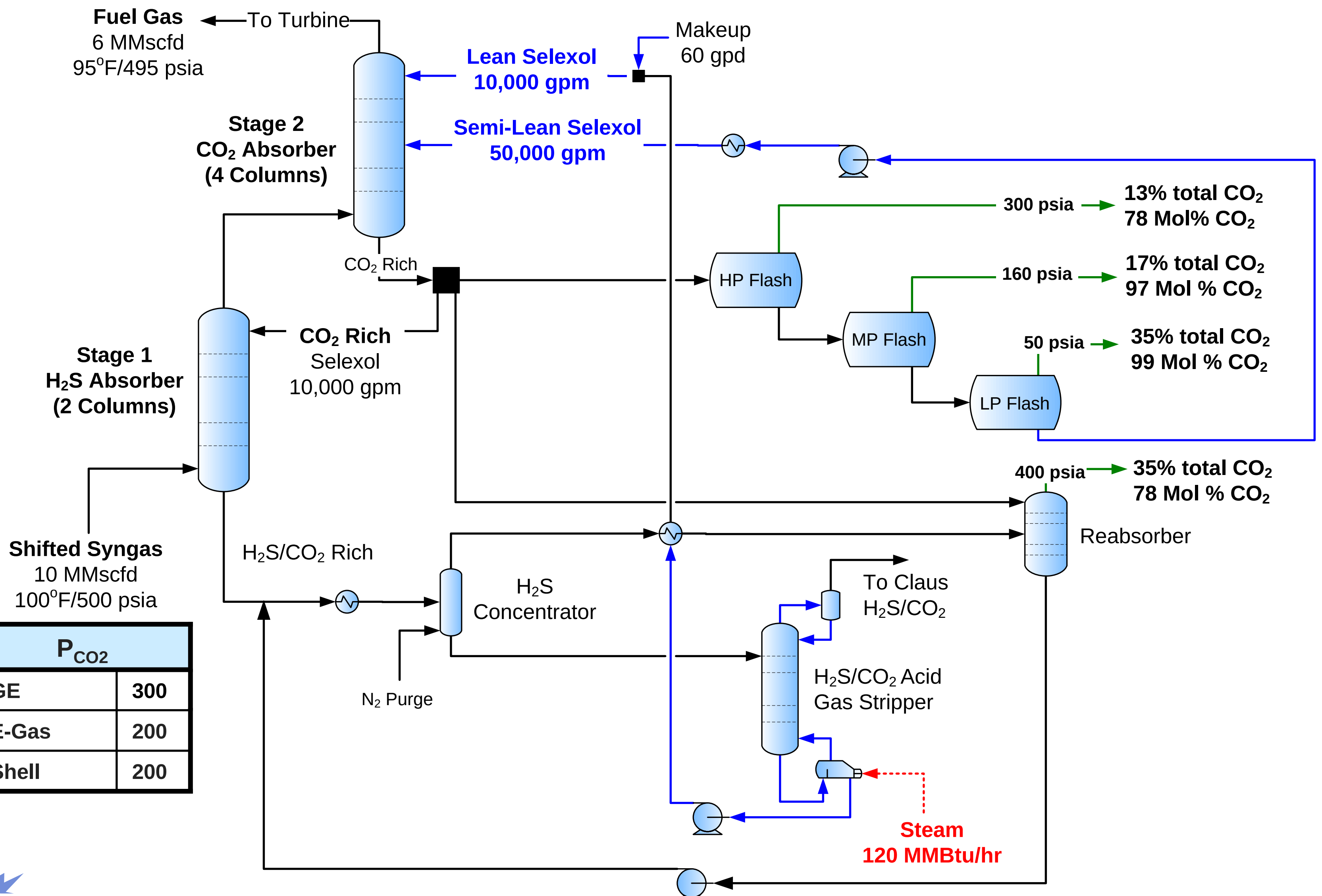
- Physical Liquid Sorbent → High loadings at high $CO_2$ partial pressure
- Highly selective for $H_2S$ and $CO_2$ → No need for separate sulfur capture system
- No heat of reaction ($\Delta H_{rxn}$), small heat of solution
- Chemically and thermally stable, low vapor pressure
- 30+ years of commercial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

## Disadvantages

- Requires Gas Cooling (to ~100$^{o}$F)
- $CO_2$ regeneration by flashing



# Selexol™ Scrubbing




| $P_{CO2}$ | |
|---|---|
| GE | 300 |
| E-Gas | 200 |
| Shell | 200 |

# IGCC Power Plant

# *Results*

# Cases 1 & 2: GE Energy Radiant Performance

| | Case 1 No Capture | Case 2 Capture |
|---|---|---|
| Coal Flow Rate (Ton/day) | 5,846 | 6,063 |
| $CO_2$ Captured (Ton/day) | - | 13,120 |
| Total Gross Power (MW) | 769 | 741 |
| Auxiliary Power (MW) | | |
| Base Plant Load | 26 | 26 |
| Air Separation Unit | 96 | 115 |
| Gas Cleanup/$CO_2$ Capture | 3 | 8 |
| $CO_2$ Compression | - | 29 |
| Total Auxiliary Load (MW) | 125 | 178 |
| Net Power (MW) | 644 | 563 |
| Net Heat Rate (Btu/kWh) | 8,832 | 10,463 |
| Efficiency (% HHV) | 38.6 | 32.6 |
| Energy Penalty (%)[1] | - | 16% |

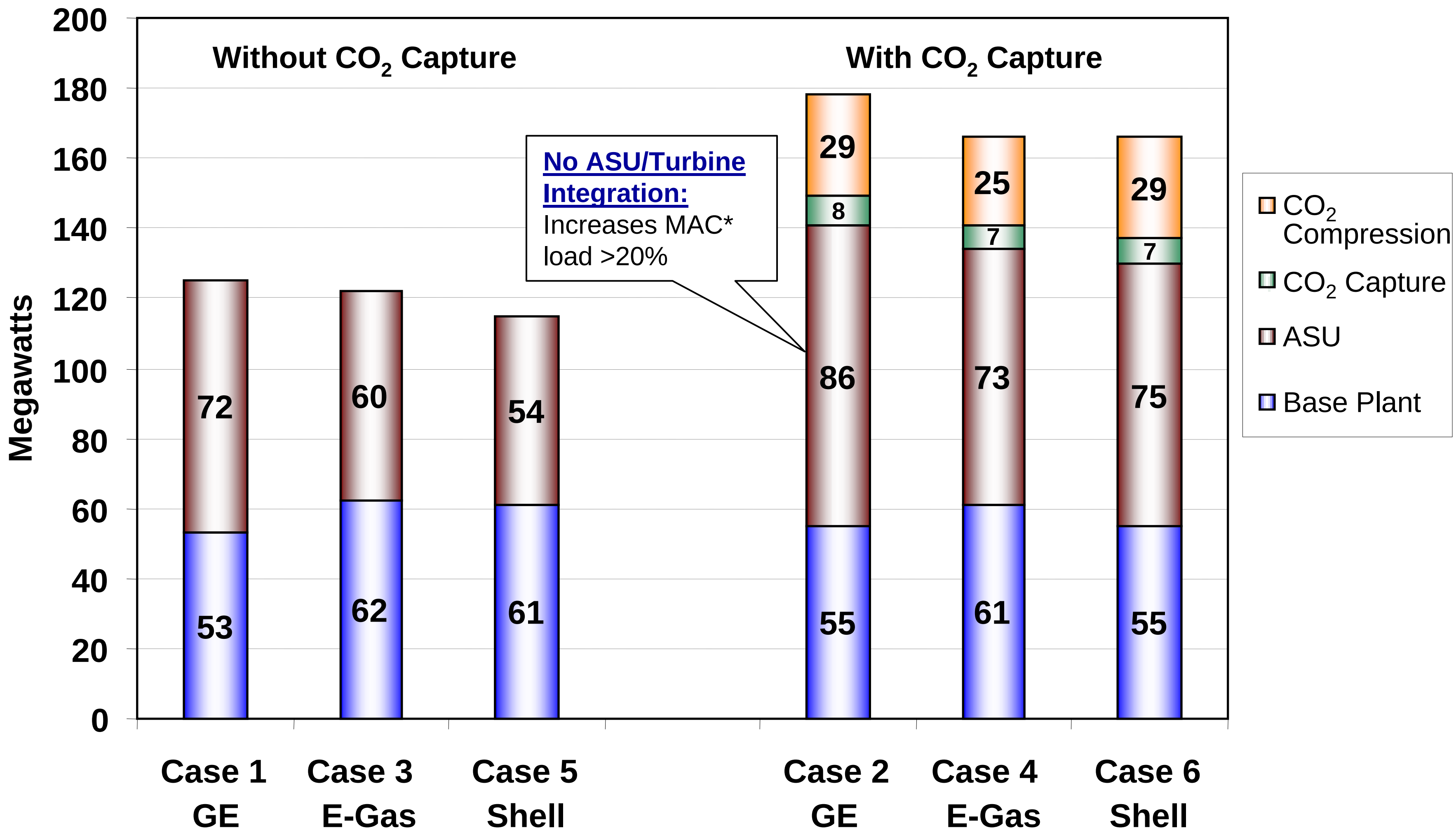
**Steam for Capture**

**- Additional $O_2$**
**- ↑ in ASU air comp. load w/o CT integ.**

**Includes $H_2S$/COS Removal in Selexol Solvent**

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

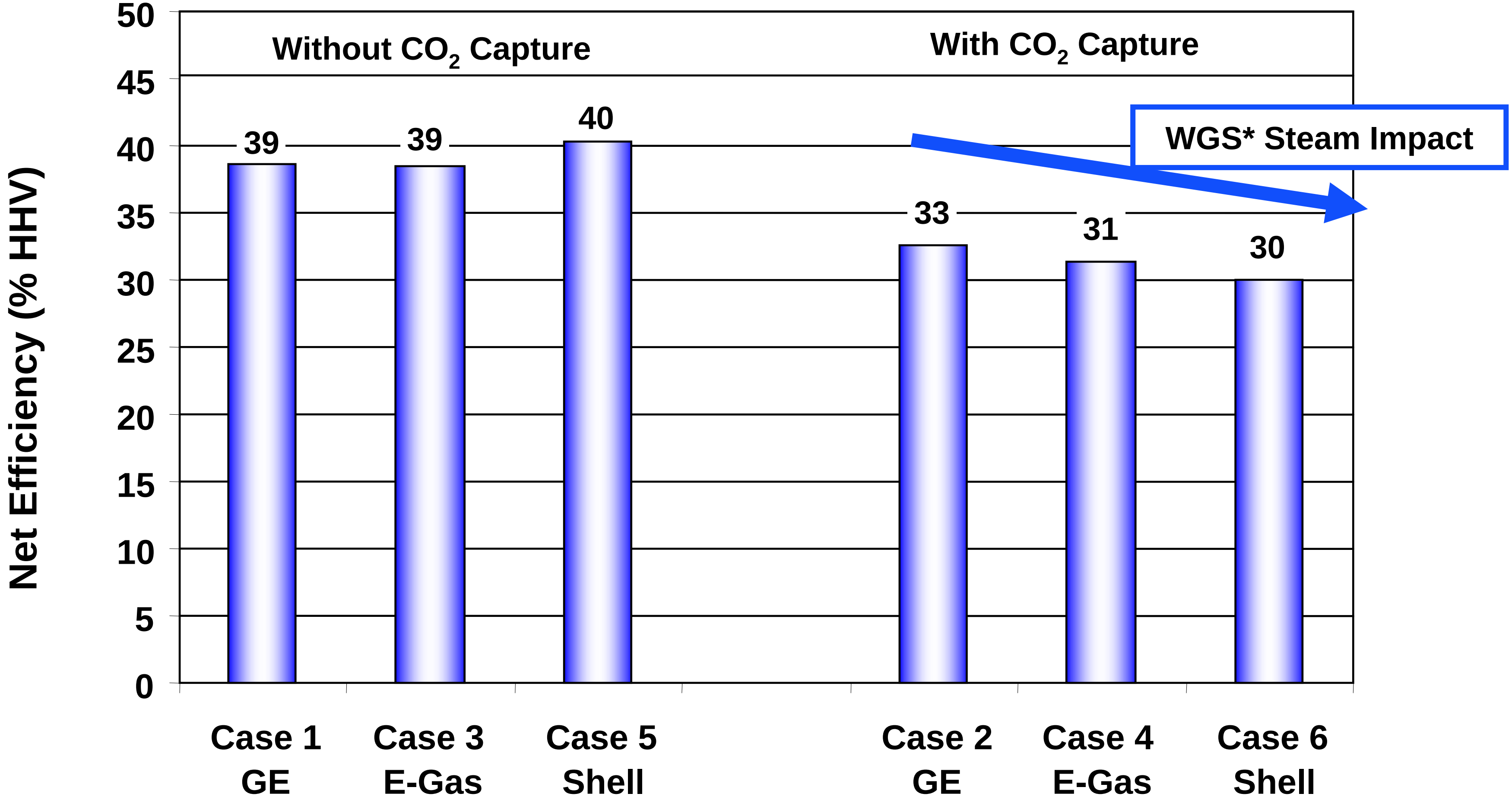
# IGCC Auxiliary Load Summary




*main air compressor

# IGCC Thermal Efficiency Summary

**$CO_2$ Capture decreases net efficiency by 6-10 percentage points**




*Water Gas Shift

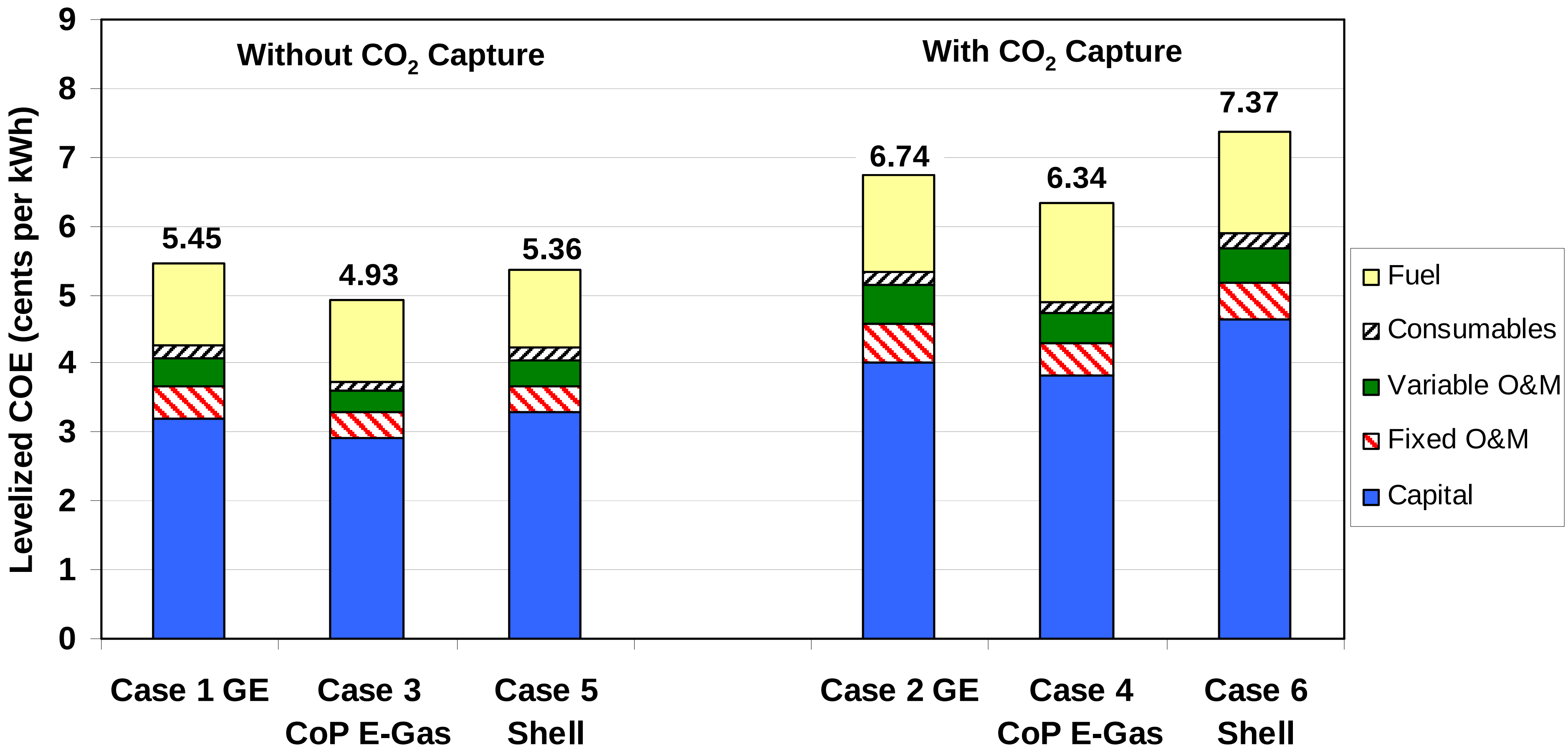
# Cases 1 & 2: GE Energy Radiant Economics

| | Case 1 No Capture | Case 2 Capture | Difference |
|---|---|---|---|
| **Plant Cost ($/kWe)[1]** | | | |
| **Base Plant** | 1,311 | 1,457 | 146 |
| **Air Separation Unit** | 100 | 165 | 65 |
| **Gas Cleanup/$CO_2$ Capture** | 146 | 262 | 116 |
| **$CO_2$ Compression** | - | 66 | 66 |
| **Total Plant Cost ($/kWe)** | 1,557 | 1,950 | 393 |
| **Capital COE (Cents/kWh)** | 3.21 | 4.02 | 0.81 |
| **Variable COE (Cents/kWh)** | 2.24 | 2.72 | 0.48 |
| **Total COE (Cents/kWh)[2]** | 5.45 | 6.74 | 1.29 |
| **Increase in COE (%)** | - | 24 | |
| **$/tonne $CO_2$ Avoided** | - | 18 | |

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

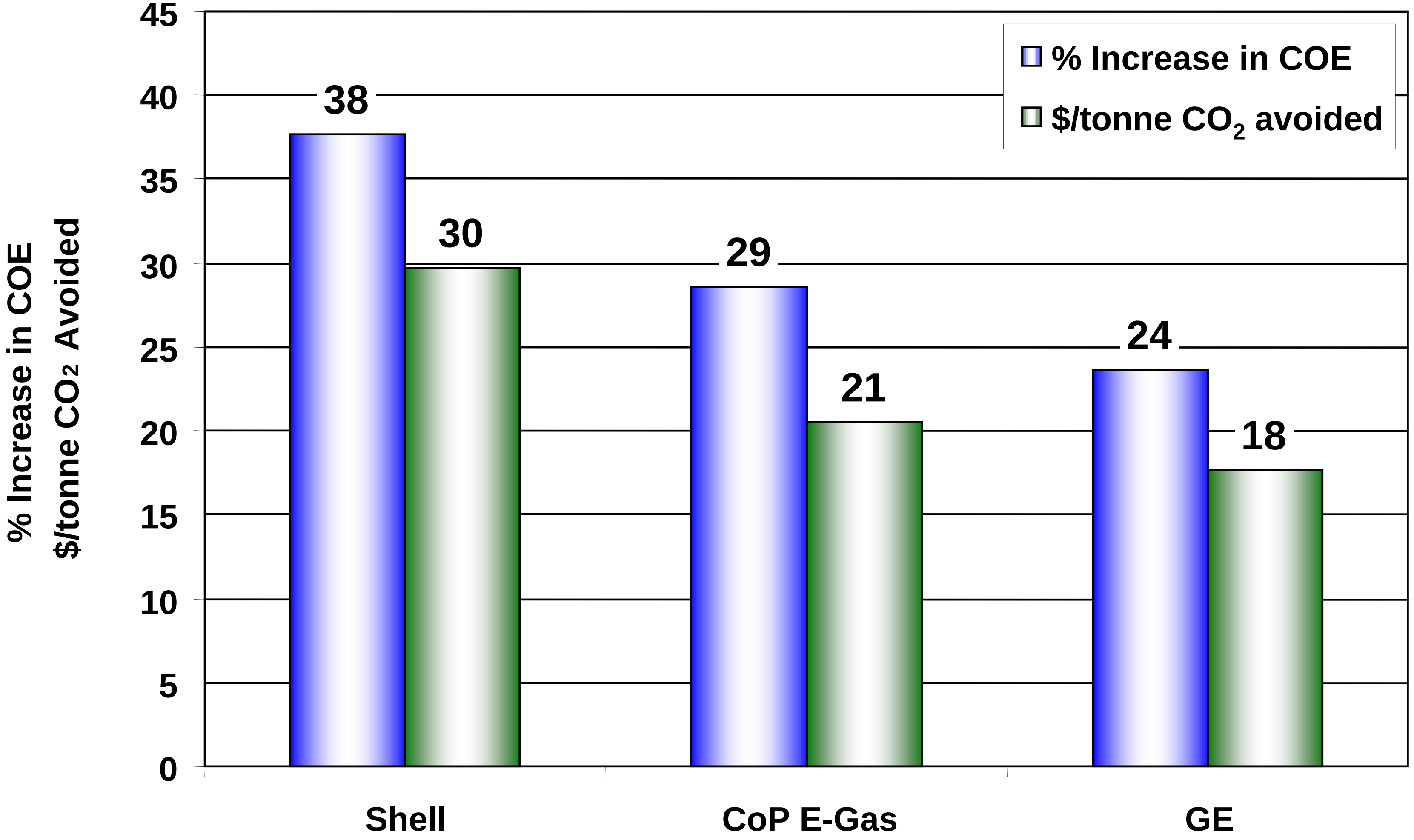
[2]January 2006 Dollars, 85% Capacity Factor, 13.8% Levelization Factor, Coal cost $1.34/10^6 Btu

# IGCC Economic Results Summary




**Average COE (cents/kWh) = 5.3 and 6.8 (w/capture)**
**Average increase in COE for $CO_2$ capture = 30%**

# IGCC $CO_2$ Capture Mitigation Cost Summary



# IGCC $CO_2$ Capture Key Points

1. **No ASU integration with $CO_2$ Capture cases, this increases ASU MAC* power load and overall ASU capital costs**
2. **Syngas $H_2O$/CO ratio has large influence on water-gas shift steam requirement, steam turbine output and net plant efficiency**
3. **CoP/E-Gas has high methane content, with Selexol at 95% capture, can only get 89% carbon capture**

*Main Air Compressor

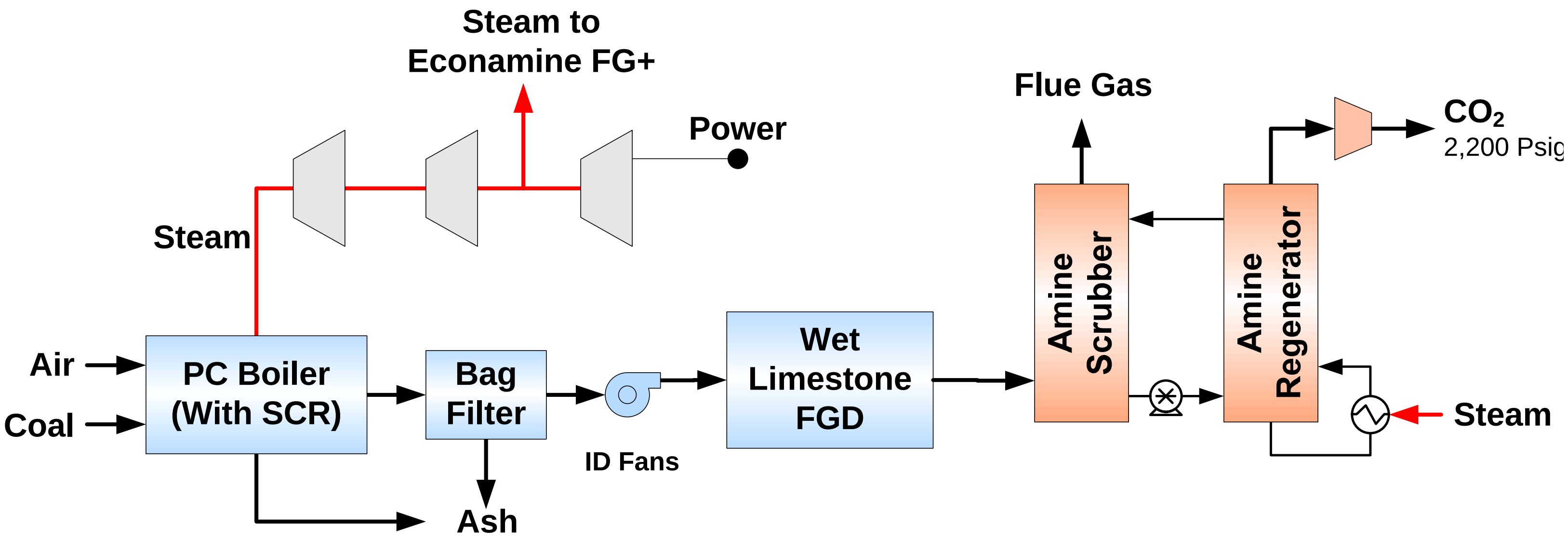
# Pulverized Coal Power Plant

# *Current State* $CO_2$ Capture Using Advanced Amines

**Post-Combustion $CO_2$ Capture Baseline**

# Post-Combustion Current Technology

## *Pulverized Coal Power Plant with $CO_2$ Scrubbing*




**PM Control:** Bag House to get 0.015 lb/MMBtu (99.8% removal)

**SOx Control:** FGD to get 0.086 lb/MMBtu (98.5% removal)

**NOx Control:** LNB + OFA + SCR to maintain 0.7 lb/MMBtu

**Mercury Control:** Activated Carbon Injection

**Steam Conditions (Subcritical) - 2400 psig/1050°F/1050°F**

**Steam Conditions (Supercritical) - 3500 psig/1100°F/1100°F**

# 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**

## Amine Disadvantages

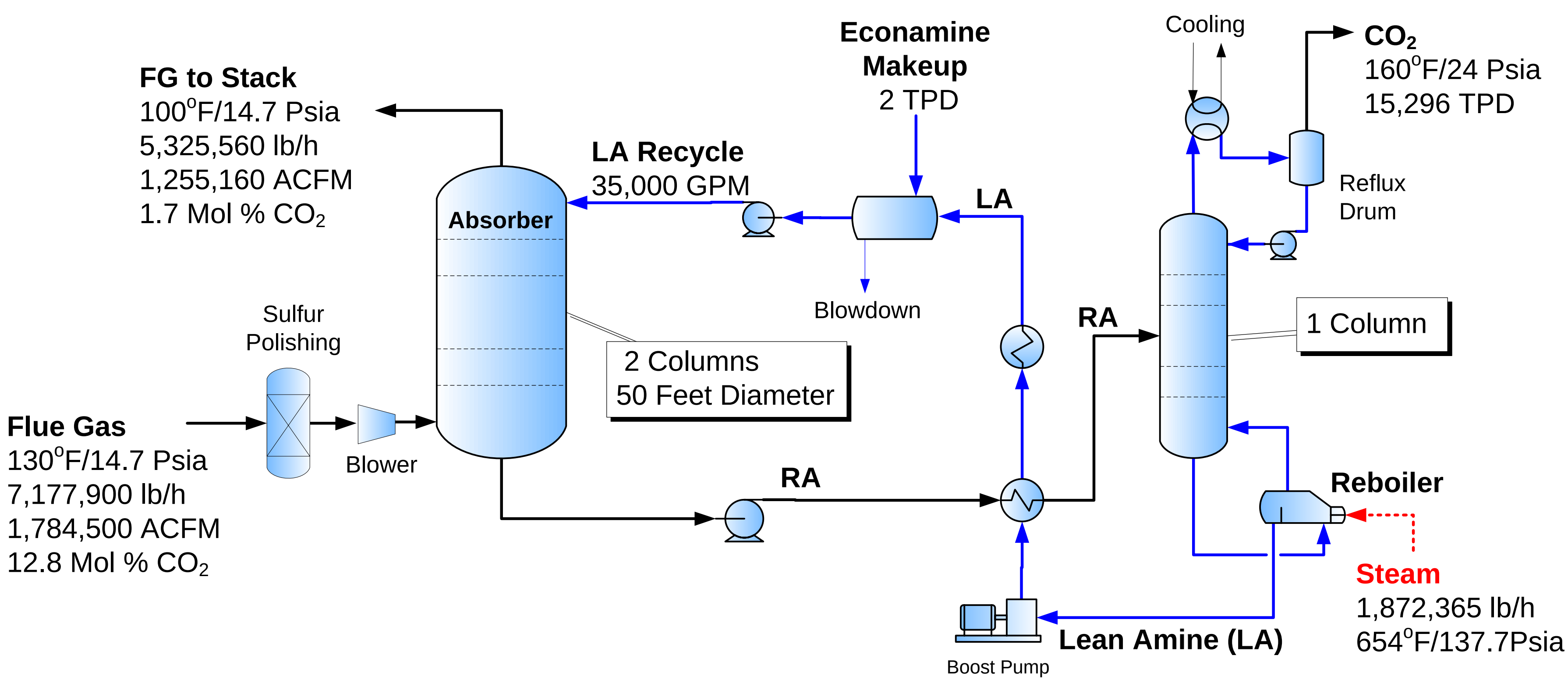
1. **High heat of reaction → high regeneration energy required**
   - 1,500 to 3,500 Btu/lb $CO_2$ removed
2. **Degradation and Corrosion**
   - Requires 10 ppm sulfur or less

# Amine Scrubbing Improvements

***Amine $CO_2$ scrubbing technology leaders are Fluor (Econamine FG Plus$^{SM}$) and Mitsubishi (KS)***

| Improvements | Benefits | Outcome |
|---|---|---|
| 1. New Solvent Formulation | ↑ Reaction Rates | ↓ Packing volume, ↓ Absorber size<br>↓ Absorber cost |
| | ↑ $CO_2$ Capacity | ↓ Solvent circulation, ↓ Reboiler Duty |
| 2. Heat Integration | ↑ Reaction Rates | ↓ Packing volume, ↓ Absorber size<br>↓ 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 $CO_2$) | 1,530 | Regeneration (°F) | 250's |
| MEA Circulation Rate (GPM) | 35,000 | Auxiliary Power (MW) | 22-25 |
| Absorption (°F) | 100's | Induced Draft Fan (MW) | 13-15 |

# Pulverized Coal Power Plant

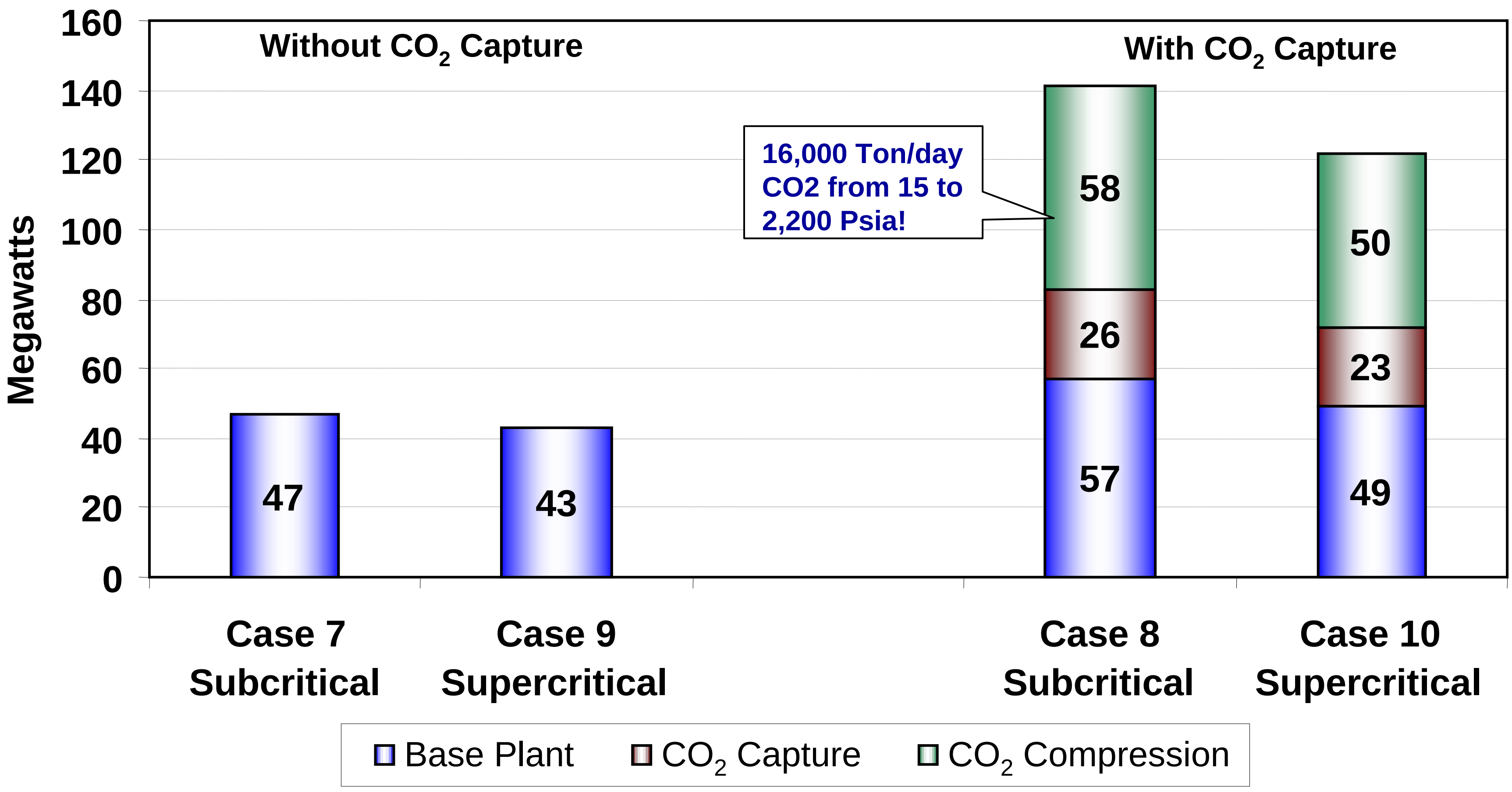
## *Results*

# Pulverized Coal Combustion Performance

| | Subcritical | | Supercritical | |
|---|---|---|---|---|
| | No Capture | Capture | No Capture | Capture |
| Coal Flow Rate (Ton/day) | 5,310 | 8,069 | 5,013 | 7,091 |
| $CO_2$ Captured (Ton/day) | - | 15,880 | - | 14,620 |
| Total Gross Power (MW) | 597 | 690 | 593 | 672 |
| Auxiliary Power (MW) | | | | |
| Base Plant Load | 27 | 31 | 24 | 27 |
| Forced + Induced Draft Fans | 13 | 19 | 12 | 17 |
| $CO_2$ Capture | - | 25 | | 22 |
| $CO_2$ Compression | - | 58 | - | 49 |
| Flue Gas Cleanup | 7 | 7 | 7 | 7 |
| Total Auxiliary Load (MW) | 47 | 140 | 43 | 122 |
| Net Power (MW) | 550 | 550 | 550 | 550 |
| Net Heat Rate (Btu/kWh) | 9,389 | 14,274 | 8,857 | 12,517 |
| Efficiency (% HHV) | 36 | 24 | 39 | 27 |
| $CO_2$ Energy Penalty (%)[1] | - | 33 | - | 31 |

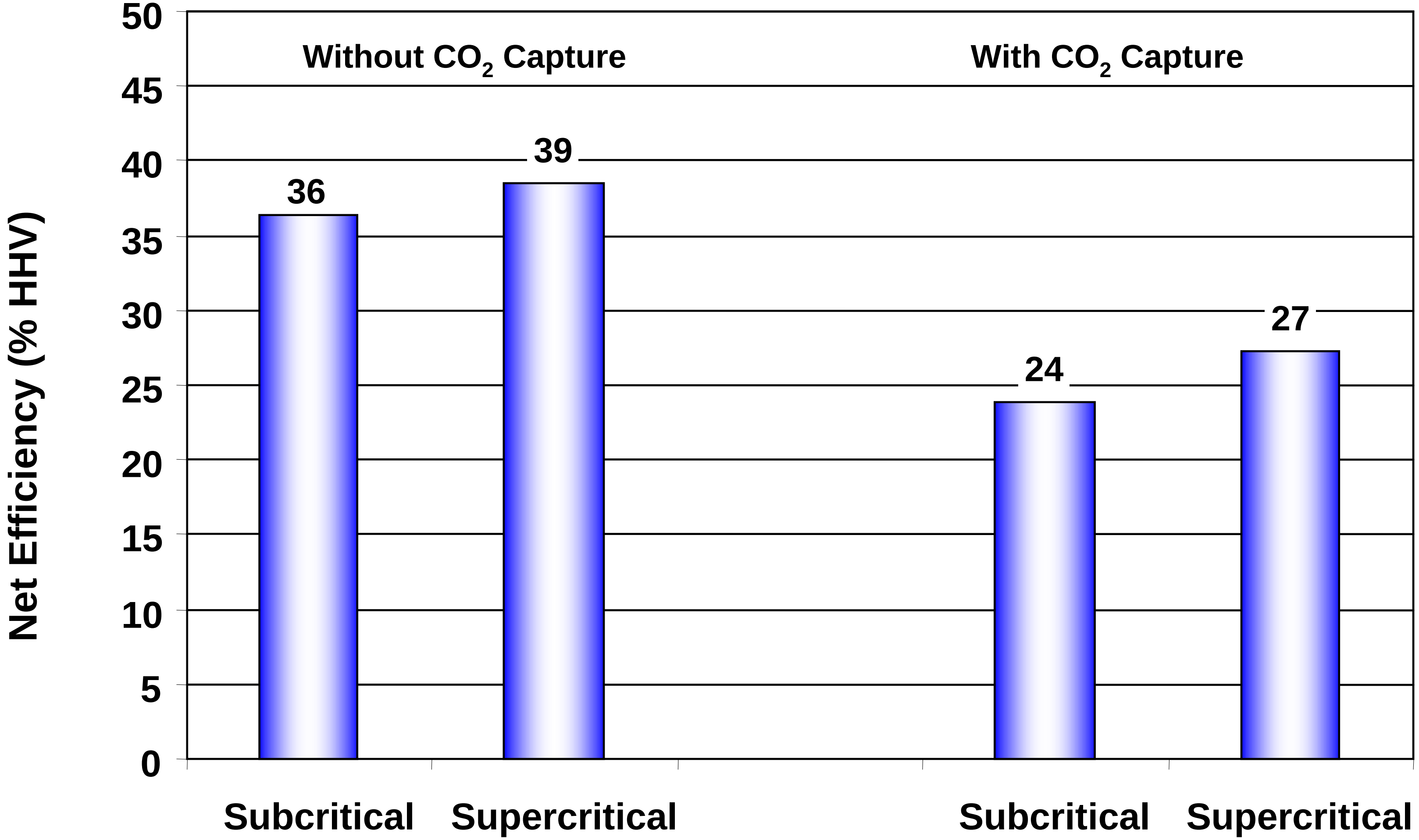
[1]$CO_2$ Capture Energy Penalty = Percent decrease in net power plant efficiency due to $CO_2$ capture

# Pulverized Coal Auxiliary Load Summary



# Pulverized Coal Thermal Efficiency Summary

**$CO_2$ capture decreases net efficiency by 12 percentage points**



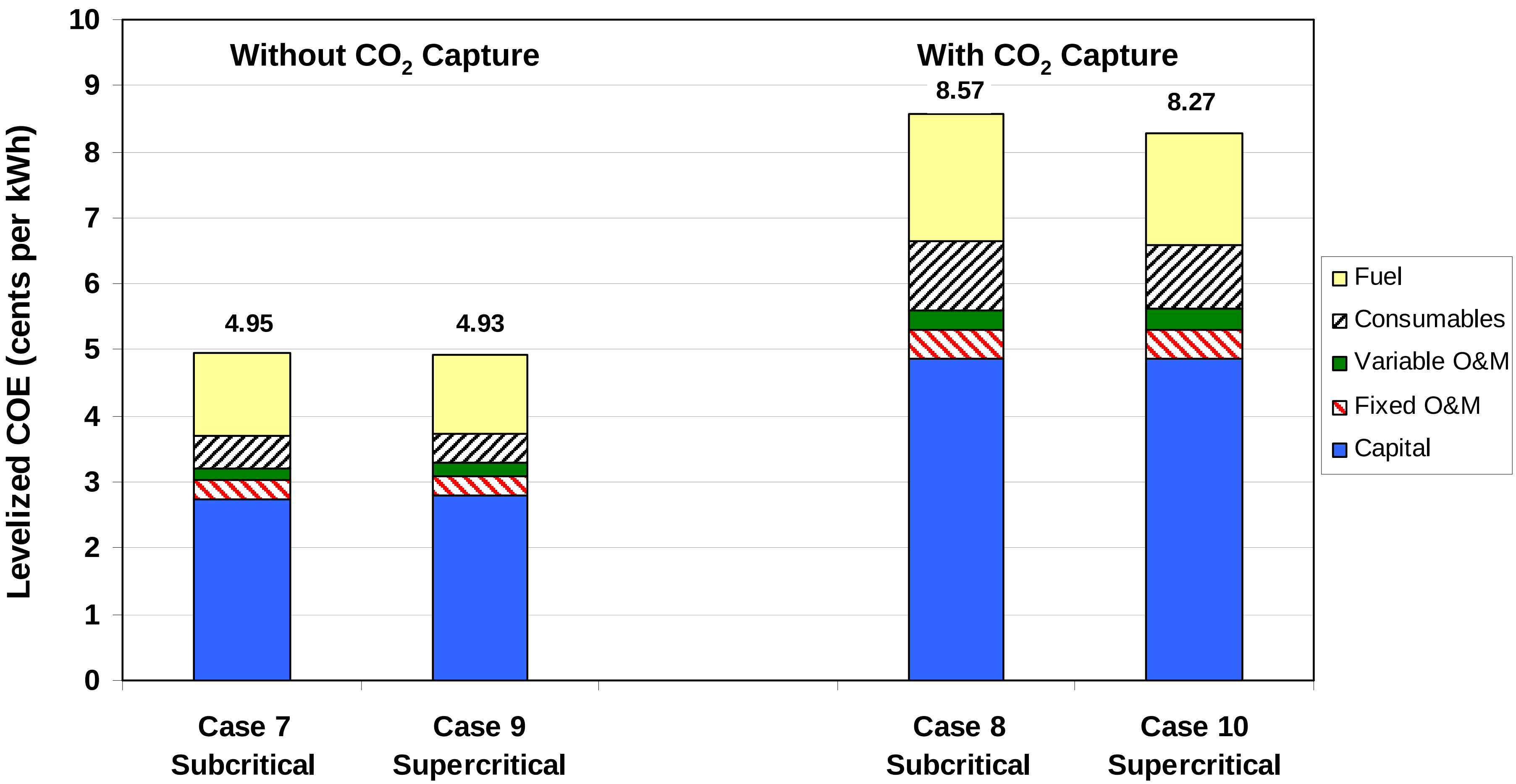
# Pulverized Coal Combustion Economics

| | Subcritical | | Supercritical | |
|---|---|---|---|---|
| | No Capture | Capture | No Capture | Capture |
| Plant Cost ($/kWe)[1] | | | | |
| Base Plant | 1,117 | 1,367 | 1,159 | 1,661 |
| $CO_2$ Capture | - | 624 | - | 622 |
| $CO_2$ Compression | - | 82 | - | 82 |
| SOx and NOx Cleanup | 206 | 285 | 196 | 257 |
| Total Plant Cost ($/kWe) | 1,323 | 2,358 | 1,355 | 2,365 |
| Capital COE (Cents/kWh) | 2.73 | 4.87 | 2.79 | 4.87 |
| Variable COE (Cents/kWh) | 2.22 | 3.70 | 2.14 | 3.39 |
| Total COE (Cents/kWh)[2] | 4.95 | 8.57 | 4.94 | 8.27 |
| Increase in COE (%) | - | 73 | - | 67 |
| $/tonne $CO_2$ Avoided | - | 49 | - | 48 |

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

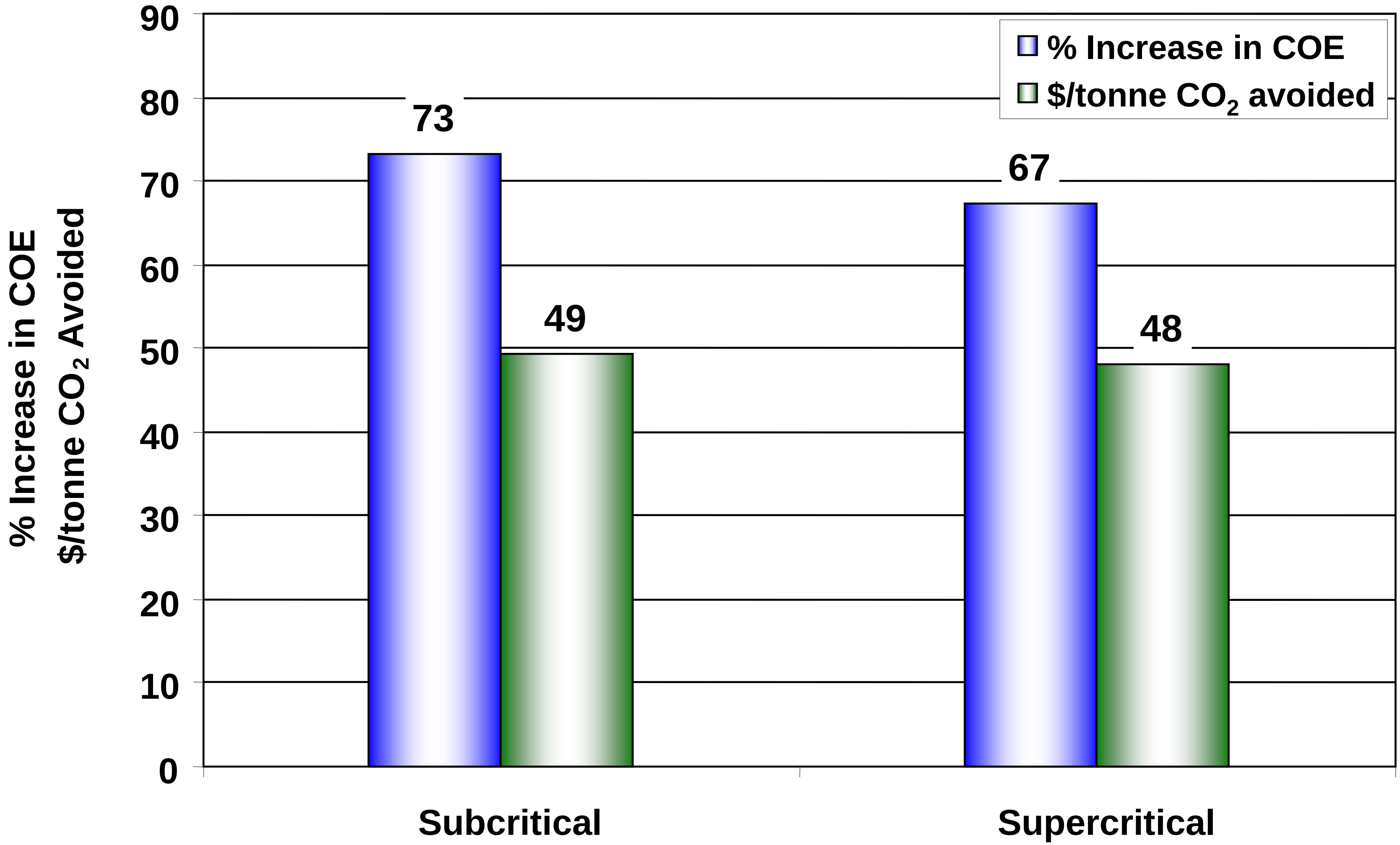
[2]January 2006 Dollars, 85% Capacity Factor, 13.8% Levelization Factor, Coal cost $1.34/10$^6$ Btu

# Pulverized Coal Summary Results




**PC $CO_2$ capture average increase in COE = 70%**

# Pulverized Coal $CO_2$ Capture Mitigation Costs



# 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
    - Good opportunity for R&D

2. **"Post-combustion $CO_2$ capture processes can be regarded as *current technology*, but some demonstration of these technologies at large scale coal fired power plants is needed before they can be widely adopted with an acceptable level of commercial risk." (IEA 2004)**

# Acknowledgements


- **NETL Team**
  - Juli Klara – Subtask Manager
  - Jared Ciferno – Technical Monitor
  - Mike Reed – Technical Monitor
- **RDS Team**
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  - Mike Rutkowski (Parsons Corporation) – Technical
  - Vlad Vaysman (WorleyParsons) – Technical
  - Tom Buchanan (WorleyParsons) – Cost
  - Massood Ramezan (SAIC) – Subtask Manager

# Thank You!

# Cases 3 & 4: ConocoPhillips E-Gas™ Performance

| | Case 3 No Capture | Case 4 Capture |
|---|---|---|
| Coal Flow Rate (Ton/day) | 5,583 | 5,768 |
| $CO_2$ Captured (Ton/day) | - | 11,870 |
| Total Gross Power (MW) | 734 | 680 |
| Auxiliary Power (MW) | | |
| Base Plant Load | 29 | 29 |
| Air Separation Unit | 91 | 103 |
| Gas Cleanup/$CO_2$ Capture | 2 | 7 |
| $CO_2$ Compression | - | 27 |
| Total Auxiliary Load (MW) | 122 | 166 |
| Net Power (MW) | 612 | 515 |
| Net Heat Rate (Btu/kWh) | 8,870 | 10,895 |
| Efficiency (% HHV) | 38.5 | 31.3 |
| $CO_2$ Energy Penalty (%)[1] | - | 19 |

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

# Cases 3 & 4: ConocoPhillips E-Gas™ Economics

| | Case 3 No Capture | Case 4 Capture | Difference |
|---|---|---|---|
| **Plant Cost ($/kWe)**[1] | | | |
| Base Plant | 1,173 | 1,399 | 226 |
| Air Separation Unit | 133 | 158 | 25 |
| Gas Cleanup/$CO_2$ Capture | 111 | 237 | 126 |
| $CO_2$ Compression | - | 67 | 67 |
| **Total Plant Cost ($/kWe)** | 1,417 | 1,861 | 444 |
| **Capital COE (Cents/kWh)** | 2.92 | 3.83 | 0.91 |
| **Variable COE (Cents/kWh)** | 2.01 | 2.51 | 0.50 |
| **Total COE (Cents/kWh)**[2] | 4.93 | 6.34 | 1.41 |
| **Increase in COE (%)** | - | 29 | |
| **$/tonne $CO_2$ Avoided** | | 21 | |

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

[2]January 2006 Dollars, 85% Capacity Factor, 13.8% Levelization Factor, Coal cost $1.34/10^6 Btu

# Cases 5 & 6: Shell Gasification Performance

| | Case 5 No Capture | Case 6 Capture |
|---|---|---|
| Coal Flow Rate (Ton/day) | 5,401 | 5,743 |
| $CO_2$ Captured (Ton/day) | - | 12,430 |
| Total Gross Power (MW) | 736 | 667 |
| Auxiliary Power (MW) | | |
| Base Plant Load | 25 | 23 |
| Air Separation Unit | 90 | 107 |
| Gas Cleanup/$CO_2$ Capture | 1 | 7 |
| $CO_2$ Compression | - | 29 |
| Total Auxiliary Load (MW) | 115 | 166 |
| Net Power (MW) | 621 | 501 |
| Net Heat Rate (Btu/kWh) | 8,468 | 11,156 |
| Efficiency (% HHV) | 40.3 | 30.6 |
| $CO_2$ Energy Penalty (%)[1] | - | 25 |

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

# Cases 5 & 6: Shell Gasification Economics

| | Case 5 No Capture | Case 6 Capture | Difference |
|---|---|---|---|
| Plant Cost ($/kWe)[1] | | | |
| Base Plant | 1,354 | 1,726 | 372 |
| Air Separation Unit | 124 | 154 | 30 |
| Gas Cleanup/$CO_2$ Capture | 115 | 302 | 187 |
| $CO_2$ Compression | - | 70 | 70 |
| Total Plant Cost ($/kWe) | 1,593 | 2,252 | 659 |
| Capital COE (Cents/kWh) | 3.28 | 4.63 | 1.35 |
| Variable COE (Cents/kWh) | 2.08 | 2.74 | 0.66 |
| Total COE (Cents/kWh)[2] | 5.36 | 7.38 | 2.02 |
| Increase in COE (%) | - | 38 | |
| $/tonne $CO_2$ Avoided | | 30 | |

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

[2]January 2006 Dollars, 85% Capacity Factor, 13.8% Levelization Factor, Coal cost $1.34/10^6$ Btu

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