# $CO_2$ Capture From *Existing* Coal-Fired Power Plants

***Final Results***

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# Background—Scoping Study

**Scoping Study Objectives:**

1. Literature search on large-scale $CO_2$ capture from existing PC plants

2. Investigate all potential cost saving strategies

3. Explore definition of 'optimal' level of $CO_2$ recovery

4. Is there enough information available to calculate the optimal level of $CO_2$ recovery? If not, develop a plan for a more detailed study

# Background—Fall 2005 Scoping Study

**Question : Is there enough information in the literature to answer these questions?**

**<u>Scoping Study Objectives</u>:**

1. Literature search on large-scale $CO_2$ capture from existing PC plants
2. Identify barriers to $CO_2$ capture retrofits
3. Investigate <u>all</u> potential cost saving strategies
4. Define 'optimal' level of $CO_2$ recovery
5. Is there enough information available to calculate the optimal level of $CO_2$ recovery? If not, develop a plan for a more detailed study

# Background: Study 1

## 1991: EPRI/IEA/Fluor Daniel[1]

- New 500 MW PC Plant
- Sensitivity Studies: 50% and 20% $CO_2$ capture on new plant
- Retrofit 500 MW PC plant using MEA with 90% $CO_2$ capture

| | NEW | | | | Retrofit* |
|---|---|---|---|---|---|
| **$CO_2$ Capture, %** | **0** | **90** | **50** | **20** | **90** |
| **Gross Power, MW** | 554 | 447 | 488 | 529 | 447 |
| **Auxiliary Power, MW** | 41 | 109 | 79 | 53 | 111 |
| **Heat Rate, Btu/kWh** | 9,800 | 14,900 | 12,300 | 10,600 | 15,000 |
| **Efficiency, %** | 35 | 23 | 28 | 32 | 23 |
| **COE, cents/kWh** | 4.2 | 9.3 | 7.2 | 5.7 | 10 |
| **Increase in COE, %** | - | >100 | 71 | 36 | >100 |

Source: *Engineering and Economic Evaluation of CO2 Removal from Fossil-Fuel-Fired Power Plants,* IE-7365, Fluor Daniel, Irvine, CA., IEA, France, EPRI, Palo Alto, CA. (1991)

# Background: Source 2

## 2001: DOE-NETL/Alstom Power

- Retrofit of AEP's Conesville Unit #5 (463 MW) plant via

  1.) MEA scrubbing, 2.) Oxy-fuel combustion, 3.) MEA/MDEA scrubbing
- Minimum 90% flue gas $CO_2$ captured

***Conclusions***

- "…oxy-fuel most promising for 90% capture, but MEA and MEA/DEA scrubbing 'appears' to be cheaper at <90% capture levels…"

- "…specific investment costs are high, ranging from about **800 to1800 $/kW**…"

- "…all cases indicate significant increases to the COE as a result of $CO_2$ capture—about **6.2 cents/kWh** (2001$)"

Source: Engineering Feasibility and Economics of $CO_2$ Capture on and Existing Coal-Fired Power Plant, DOE/NETL, Pittsburgh, PA., Alstom Power, Windsor, CT. (2000)

# Background: Source 3

## 2004: Canadian Clean Coal Power Coalition/IEA GHG

- Objective: "To demonstrate that coal-fired electricity generation can effectively address all environmental issues projected in the future, including $CO_2$."
- Evaluated amine scrubbing and oxy-fuel combustion for existing PC power plants and gasification for new power plants

***Conclusions***

- Identified significant opportunities to optimize amine scrubbing efficiency via heat integration---ONLY with a New Plant!
- "…during the course of Fluor's studies it became apparent that retrofits would be less attractive than expected. Therefore, the later stages of the studies concentrated on greenfield applications for all technologies…"

Source: Canadian Clean Coal Power Coalition Studies on CO2 Capture and Storage
IEA GHG, PH 4/27 (March 2004)

# Background: Source 4

## 2004: Nexant for the $CO_2$ Capture Project (CCP)

- Cost reduction opportunities for an NGCC post-combustion retrofit system using advanced amines
- Identified 8 significant cost cutting ideas for NGCC retrofits

| | 1 | 2 | BIT |
|---|---|---|---|
| **$CO_2$ Capture, %** | **0** | **90** | **90** |
| **Net Power, MW** | 392 | 322 | 357 |
| **Efficiency, %** | 57.6 | 47.3 | 52.5 |
| **$/tonne $CO_2$ Avoided** | - | **60** → | **28.2** |

- Cost reduction is too impressive to be ignored
- Question is: Could some of Nexant's recommendations be applied to a retrofit PC power plant?

Source: CO2 Capture Project: Post-Combustion "Best Integrated Technology" (BIT) Overview
Chinn, D. (Chevron Texaco), Eimer, D. (Norsk Hydro), Hurst, P. (BP), 2004 Carbon Sequestration Conference

# Potential Cost Saving Strategies
## *Technology improvements in past 5-10 years*

| Potential Retrofit Options | Outcome/Notes |
|---|---|
| 1. Heat Integration | ↓ Steam Consumption |
| 2. Minimize equipment needed | ↓ Capital cost (ex. No flue gas cooler) |
| 3. Lower cost of materials | ↓ Capital cost (stainless vs. carbon steel) |
| 4. Structured column packing | ↓ Capital cost, ↓ Sorbent rate (ex. KS1) |
| 5. Plate-and-frame HX | ↓ Capital cost |
| 6. ANSI Pumps vs. API Pumps | ↓ Capital cost |
| 7. Vapor-recovery system | ↓ Steam Consumption |
| 8. Large diameter absorbers | ↓ # of Absorbers, ↓ Capital cost |
| 9. Advanced solvents* | ↓ Capital cost, ↓ Sorbent circ. rate (ex. KS1) |
| 10. Lower re-boiler duty | ↓ Steam Consumption |

***Example:**

**Current amines (MEA) require at least 1,600 Btu/lb $CO_2$ captured**
**Fluor Econamine FG+ requires 1,300-1,400 Btu/lb $CO_2$ captured**
**Mitsubishi's KS-1 solvent requires 1,200 Btu/lb $CO_2$ captured**

# Optimal versus Required $CO_2$ Removal

1. The capture rate that results in minimum \$/tonne $CO_2$ avoided or \$/ton $CO_2$ captured

2. Fraction $CO_2$ removed at specified COE or \$/tonne avoided

3. $\Delta COE_{retrofit}$ (x% capture) = $\Delta COE_{greenfield}$ (90% capture)

4. Carbon tax—sufficient removal rate such that incremental COE equals the carbon tax

# Scoping Study Conclusions

1. Minimal economic and performance data exists for $CO_2$ capture from *existing* pulverized coal power plants

2. Majority analyses focused on 90% $CO_2$ capture from **new** plants

3. Significant improvements in $CO_2$ scrubbing technologies in past 5-10 years

4. *Detailed Systems Analysis Recommended*

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# Carbon Sequestration From Existing Power Plants Feasibility Study

*December 2005—December 2006*

Randall Gas Technologies

# Key Challenges $CO_2$ Retrofits

1. Regeneration steam availability—can steam turbine operate at part load?
2. Major equipment modifications or redundancy
3. Sulfur—additional deep sulfur removal required for most $CO_2$ sorbents
4. Space limitations—acres needed for current scrubbing
5. Make-up power—satisfy need to maintain baseload output
6. *Scheduling outages for $CO_2$ retrofits
7. *Post-retrofit dispatch implications due to increase in COE
8. *Retrofit triggering NSPS review
9. *Proposed legislation

***Outside the scope of this analysis**

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# Detailed Systems Analysis Scope

1. Assess 30%, 50%, 70%, 90% and $CO_2$ capture levels
2. Employ scrubbing technology advances
3. Detailed steam turbine analysis by ALSTOM's steam turbine retrofit group
4. Employ $CO_2$ capture and compression heat integration
5. Site visits to specify exact equipment location
6. Include make-up power costs in economic analysis

# Design Basis: Assumptions

## Economic

| | |
|---|---|
| Dollars (Constant) | 2007 |
| Depreciation (Years) | 20 |
| Equity (%) | 55 |
| Debt (%) | 45 |
| Tax Rate (%) | 38 |
| After-tax Weighted Cost of Capital (%) | 9.67 |
| Capital Charge Factor (%) | 17.5 |
| Capacity Factor (%) | 85 |
| Make-up Power Cost (¢/kWh) | 6.40 |

$CO_2$ Transport and Storage Costs not included

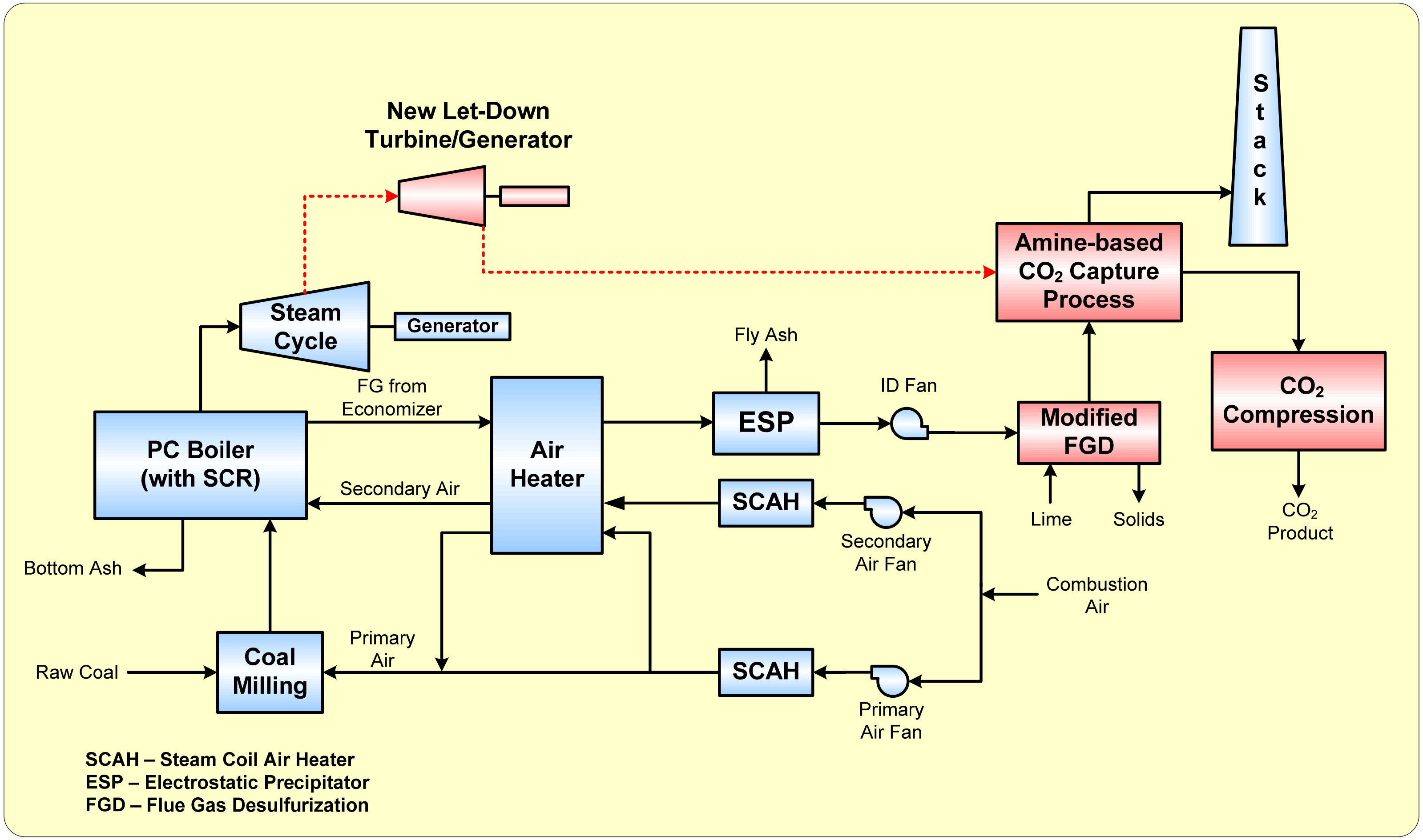
# Location: AEP Conesville Unit #5

- **Total 6 units = 2,080 MWe**
- **Unit #5:**
  - Subcritical steam cycle (2400psia/1005$^{o}$F/1005$^{o}$F)*
  - Constructed in 1976
  - 463 MW gross (~430 MW net)
  - ESP and Wet lime FGD (95% removal efficiency, 104 ppmv)

**Mid-western bituminous coal**

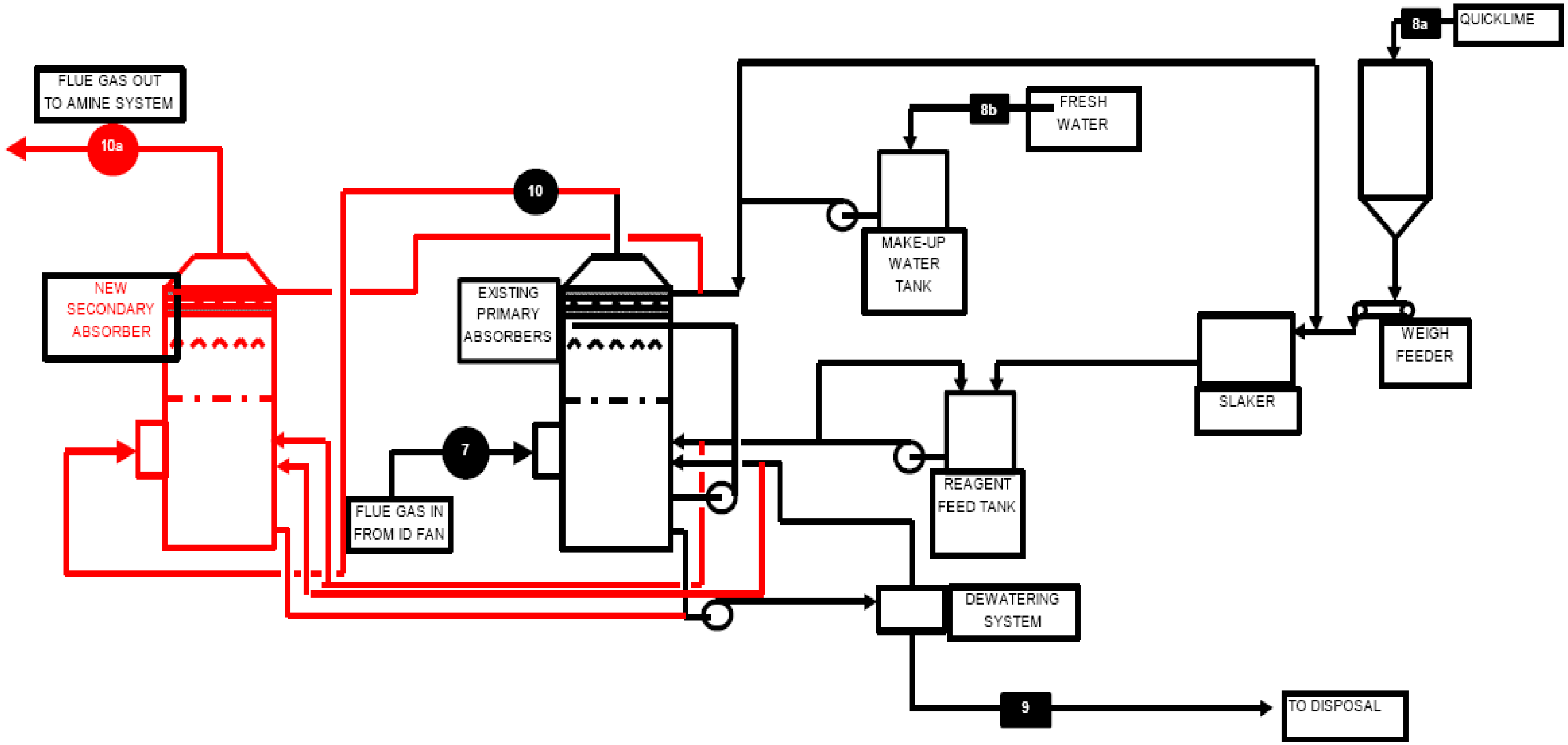
| Ultimate Analysis (wt.%) | **As Rec'd** |
|---|---|
| **Moisture** | 10.1 |
| **Carbon** | 63.2 |
| **Hydrogen** | 4.3 |
| **Nitrogen** | 1.3 |
| **Sulfur** | 2.7 |
| **Ash** | 11.3 |
| **Oxygen** | 7.1 |
| **HHV (Btu/lb)** | 11,293 |

# Existing Plant Modifications



# Modified FGD Process

1. Second stage absorber added to achieve 99.7% $SO_2$ removal efficiency (6.5 ppmv)
2. Estimated EPC cost for each case (30-90%) is $20.5MM
3. includes an $SO_2$ Credit equal to $608/ton in the Variable O&M cost



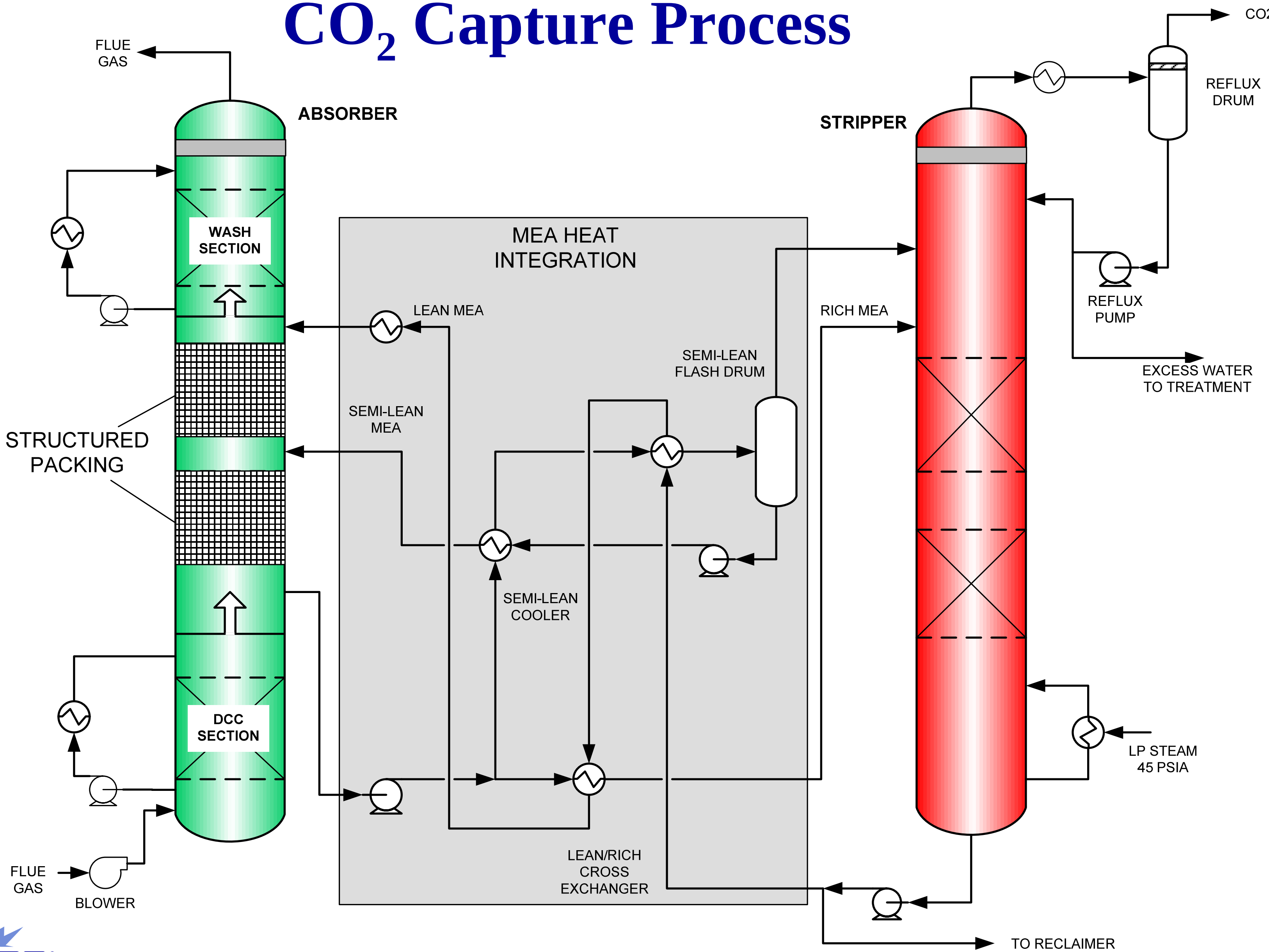
# $CO_2$ Capture Process Key Parameters

| Process Paramater | Units | 2006 | 2001 | AES Design |
|---|---|---|---|---|
| **Plant Capacity** | Ton/Day | 9,350-3,120 | 9,888 | 200 |
| **$CO_2$ Recovery** | % | 90-30 | 90 | 96 |
| **$CO_2$ in Feed** | mol % | 12.8 | 13.9 | 14.7 |
| **$SO_2$ in Feed** | ppmv | 10 (Max) | 10 (Max) | 10 (Max) |
| **Solvent** | | MEA | MEA | MEA |
| **Solvent Concentration** | Wt. % | **30** | **20** | **17-18** |
| **Lean Loading** | mol $CO_2$/mol amine | **0.19** | **0.21** | **0.10** |
| **Rich Loading** | mol $CO_2$/mol amine | **0.49** | **0.44** | **0.41** |
| **Steam Use** | lbs Steam/lb $CO_2$ | **1.67** | **2.6** | **3.45** |
| **Stripper Feed Temp** | $^oF$ | 205 | 210 | 194 |
| **Stripper Bottom Temp** | $^oF$ | 247 | 250 | 245 |
| **Feed Temp to Absorber** | $^oF$ | 115 | 105 | 108 |

Note: Additional data in "notes pages"

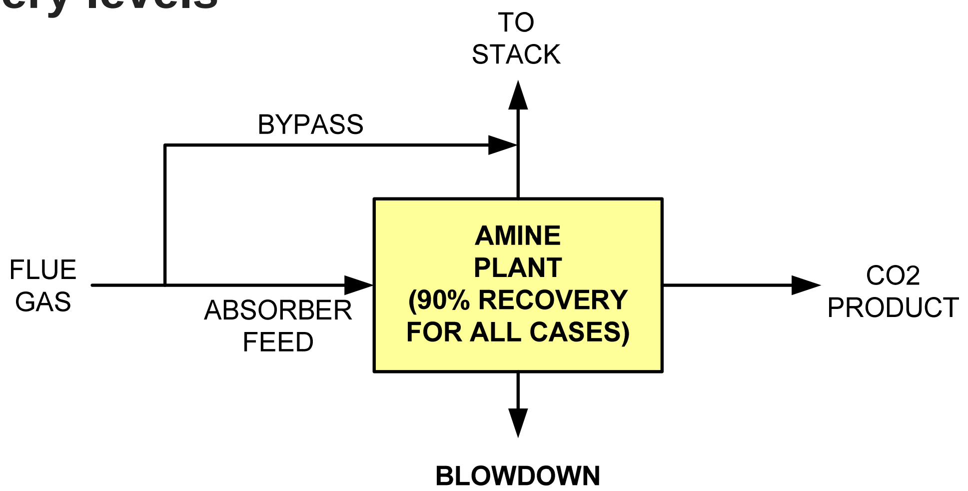
- Reboiler operated at 45 psia—reduced from 65 psia used in 2000 study
- Absorber contains two beds of structured packing

# $CO_2$ Capture Process



# Flue Gas Bypass

**Bypass method determined to be least costly method to obtain lower $CO_2$ recovery levels**




| $CO_2$ (Moles/hr) | Case 1 (90%) | Case 2 (70%) | Case 3 (50%) | Case 4 (30%) |
|---|---|---|---|---|
| **FLUE GAS** | 19,680 | 19,680 | 19,680 | 19,680 |
| BYPASS | 0 | 4,374 | 8,746 | 13,120 |
| ABSORBER FEED | 19,680 | 15,306 | 10,934 | 6,560 |
| STACK | 1,962 | 5,924 | 9,846 | 13,770 |
| $CO_2$ PRODUCT | 17,720 | 13,766 | 9,822 | 5,906 |
| # Trains | 2 | 2 | 2 | 1 |

# $CO_2$ Capture, Compression, Dehydration, and Liquefaction

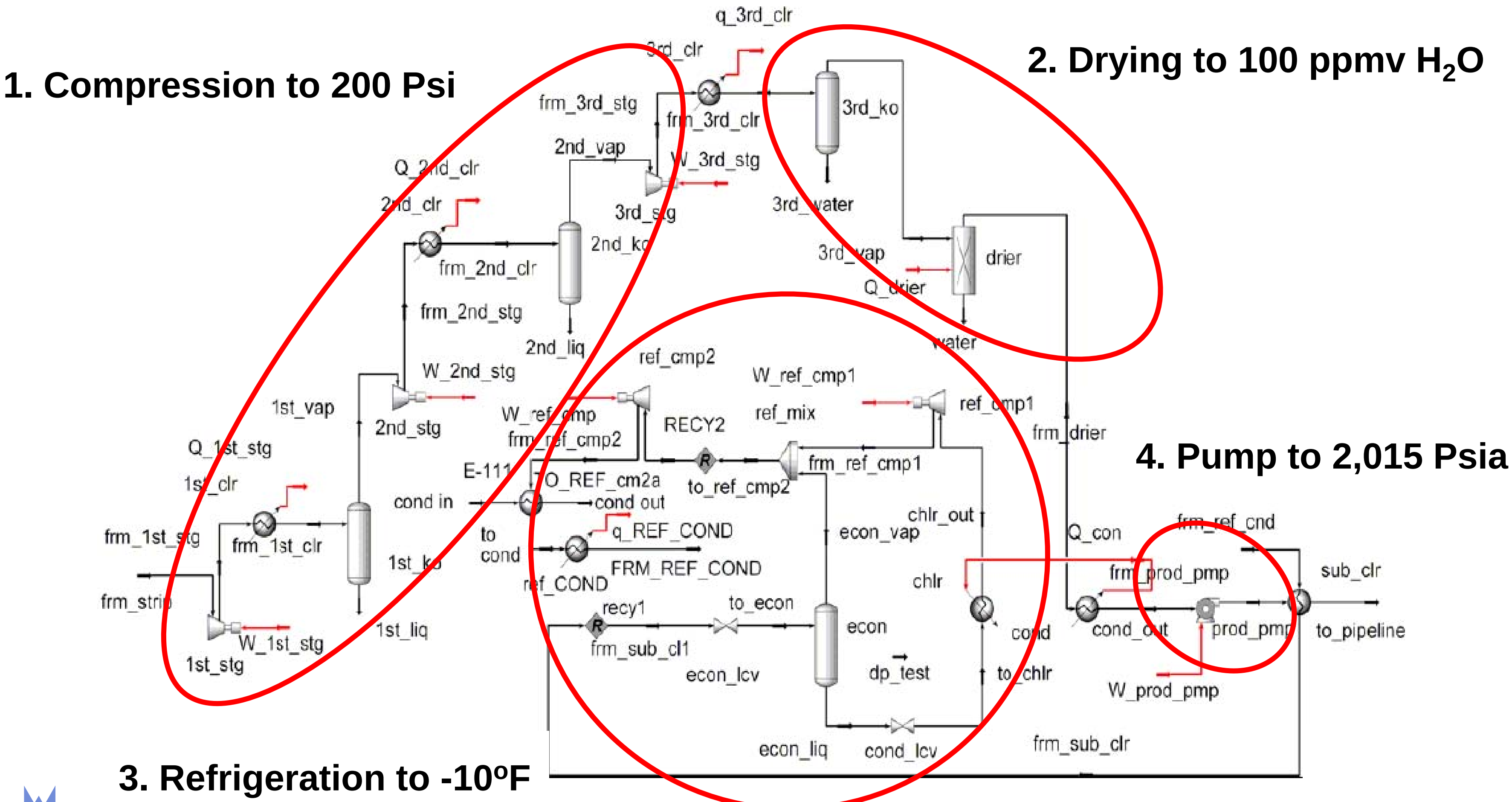
## $CO_2$ compression to 2,015 psia, EOR specifications

| Parameter | Wt % | Vol % | ppmv |
|---|---|---|---|
| Carbon Dioxide | 96 | 94.06 | 940600 |
| $C_2$+ and Hydrocarbons | 2 | 2.87 | 28700 |
| Hydrogen Sulfide | 1 | 1.27 | 12700 |
| Nitrogen | 0.6 | 0.92 | 9200 |
| Methane | 0.3 | 0.81 | 8100 |
| Oxygen | 0.03 | 0.04 | 400 |
| Mercaptans and Other Sulfides | 0.03 | 0.02 | 200 |
| Moisture | 0.006 | 0.01 | 100 |

## Four Stage Process:

**Compression ⇨ Drying ⇨ Refrigeration ⇨ Pumping**

# $CO_2$ Capture Compression, Dehydration and Liquefaction



# $CO_2$ Capture Process Equipment

| | 2007 Study | | 2001 Study | |
|---|---|---|---|---|
| **% $CO_2$ Capture** | **90** | | **96** | |
| **$CO_2$ Capture Process** | No. | ID/Height (ft) | No. | ID/Height (ft) |
| Absorber | 2 | 34/126 | 5 | 27/126 |
| Stripper | 2 | 22/50 | 9 | 16/50 |
| Distance from stack | 100 ft | | 1,500 feet | |
| | | | | |
| **Heat Exchangers** | No. | | No. | |
| Reboilers | 10 | | 9 | |
| Stripper CW Cond. | 12 | | 9 | |
| Other Heat Exchangers | 36 | | 113 | |
| **Total Heat Exchangers** | **58** | | **131** | |
| | | | | |
| **$CO_2$ Compressor** | 2 | | 7 | |
| **Propane Compressor** | 2 | | 7 | |
| | | | | |
| **TIC Cost $MM** | **370** | | **670** | |

**$CO_2$ scrubbing technology improvements lead to significant decrease in equipment requirements and capital cost!**

# Steam Turbine Modifications

**Design Assumptions:**

1. **Existing turbine/generator required to operate at maximum load in case of a trip of the MEA plant**
   – All pressures to be within a level that no steam will be blown off

2. **Feedwater system modifications to allow $CO_2$ capture and compression system heat integration**
   – $CO_2$ compressor intercoolers, stripper overhead cooler, refrigeration compressor cooler

3. **Well within the LP turbine "lower load limit" after significant steam extraction for the 90% case (Conesville #5 instruction manual)**

4. **New Let Down turbine vs. modifying existing LP turbine**

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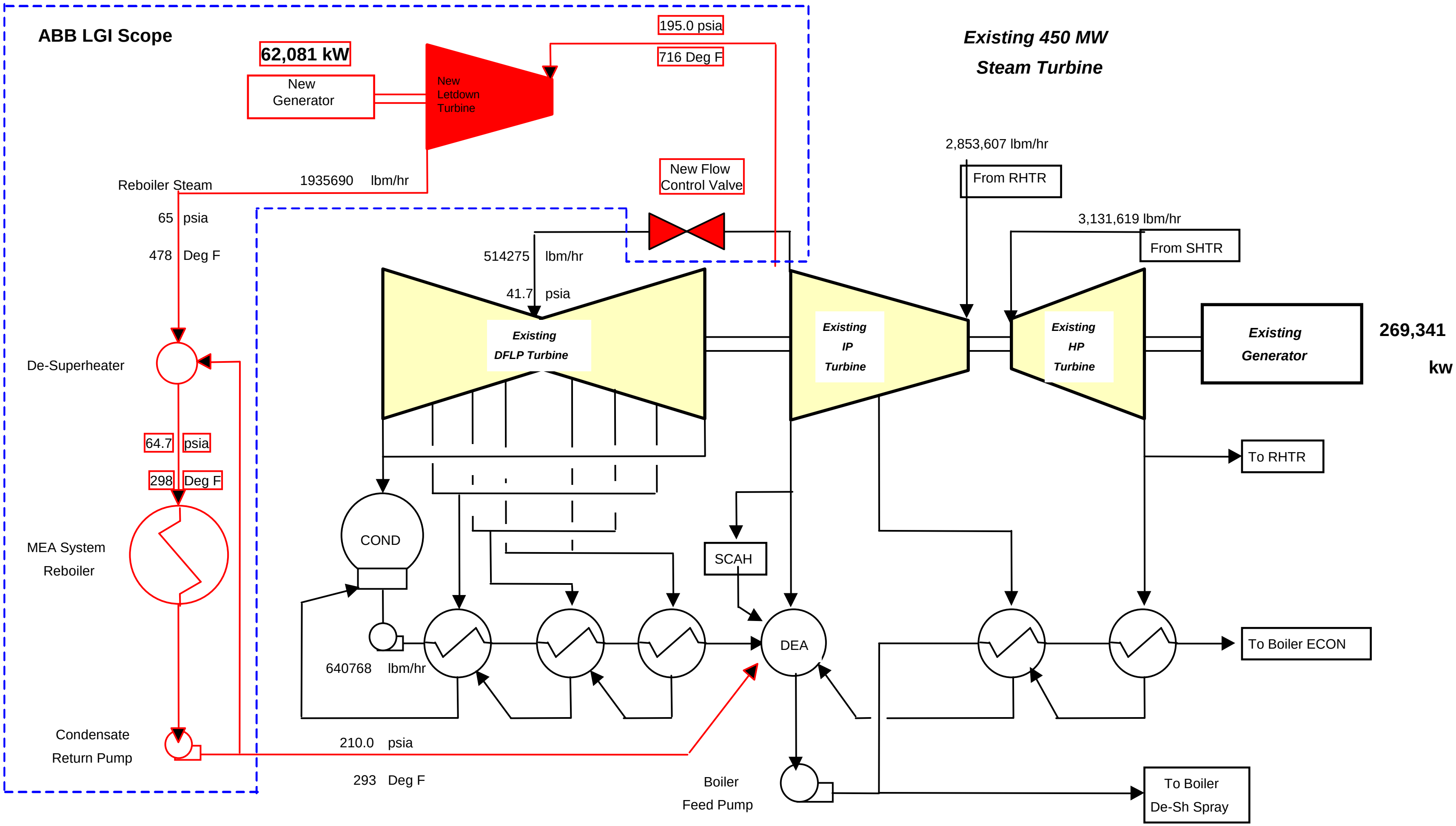
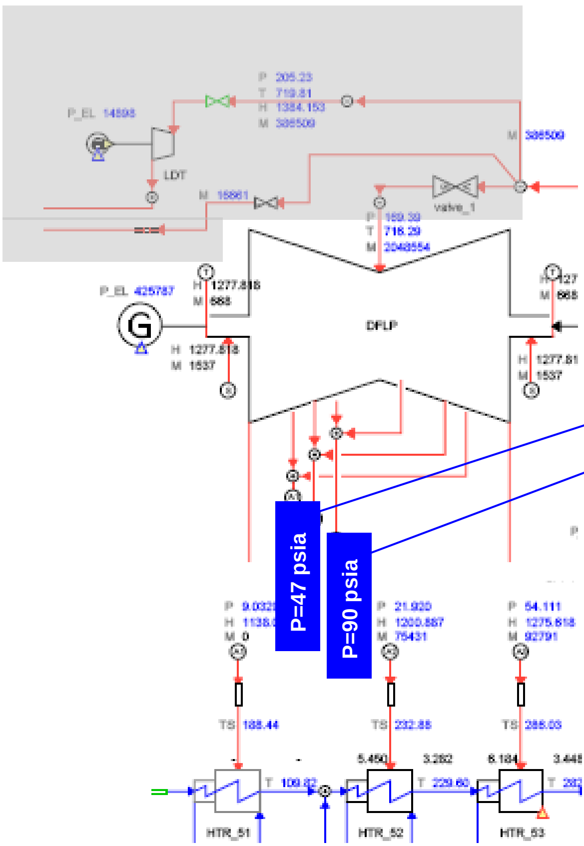
# Steam Turbine Modifications

## *New Let Down Turbine*

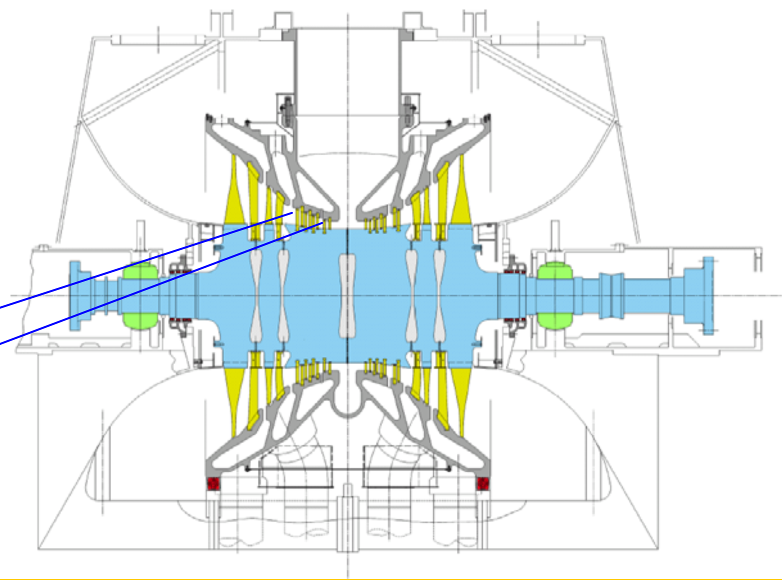



1. New LT output between 15 MW (30%) and 62 MW (90%)
2. EPC Cost ~ $10MM for each case

# Steam Turbine Modifications
## *Alternatives to LDT?*

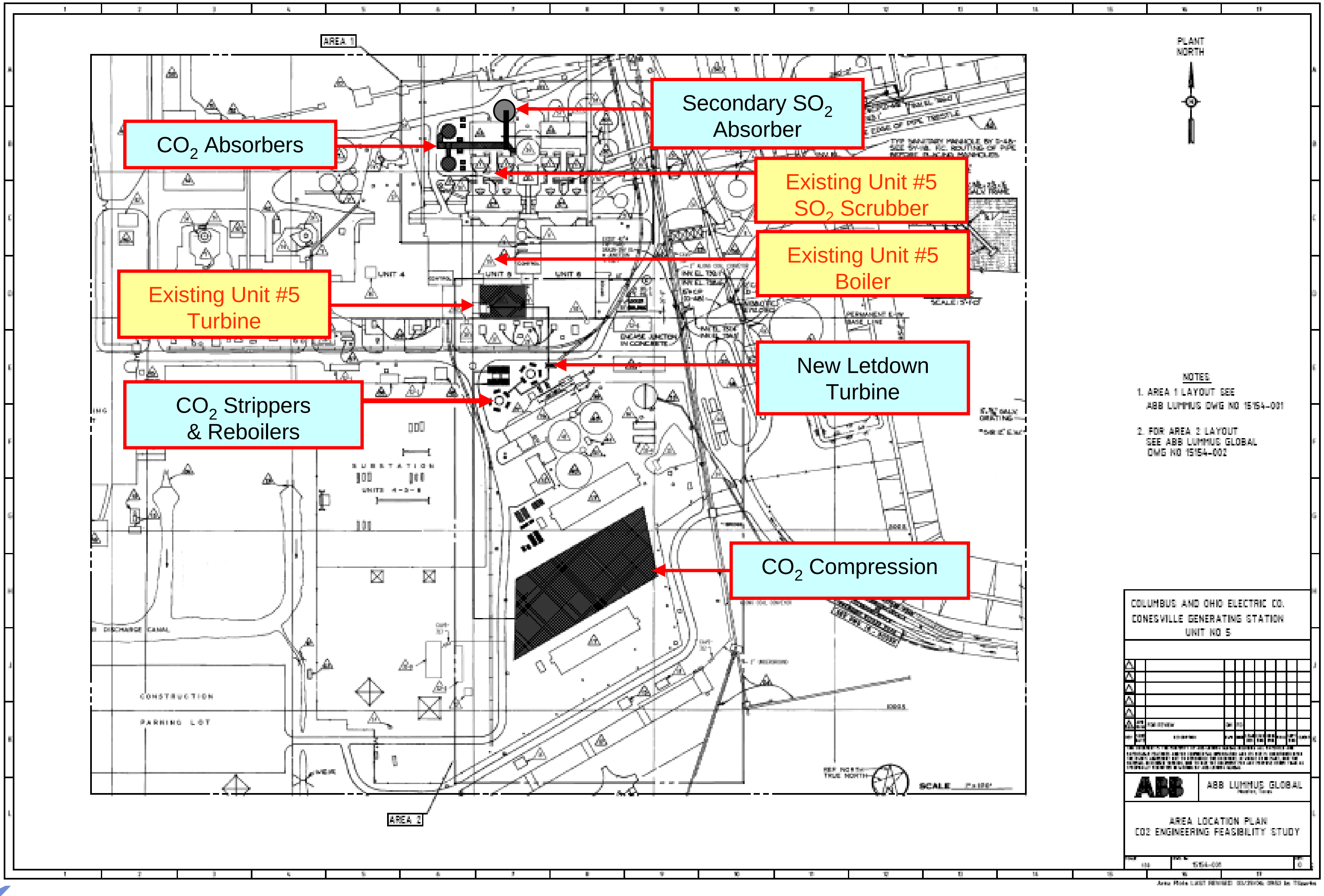



Retrofit solution for 30% Case

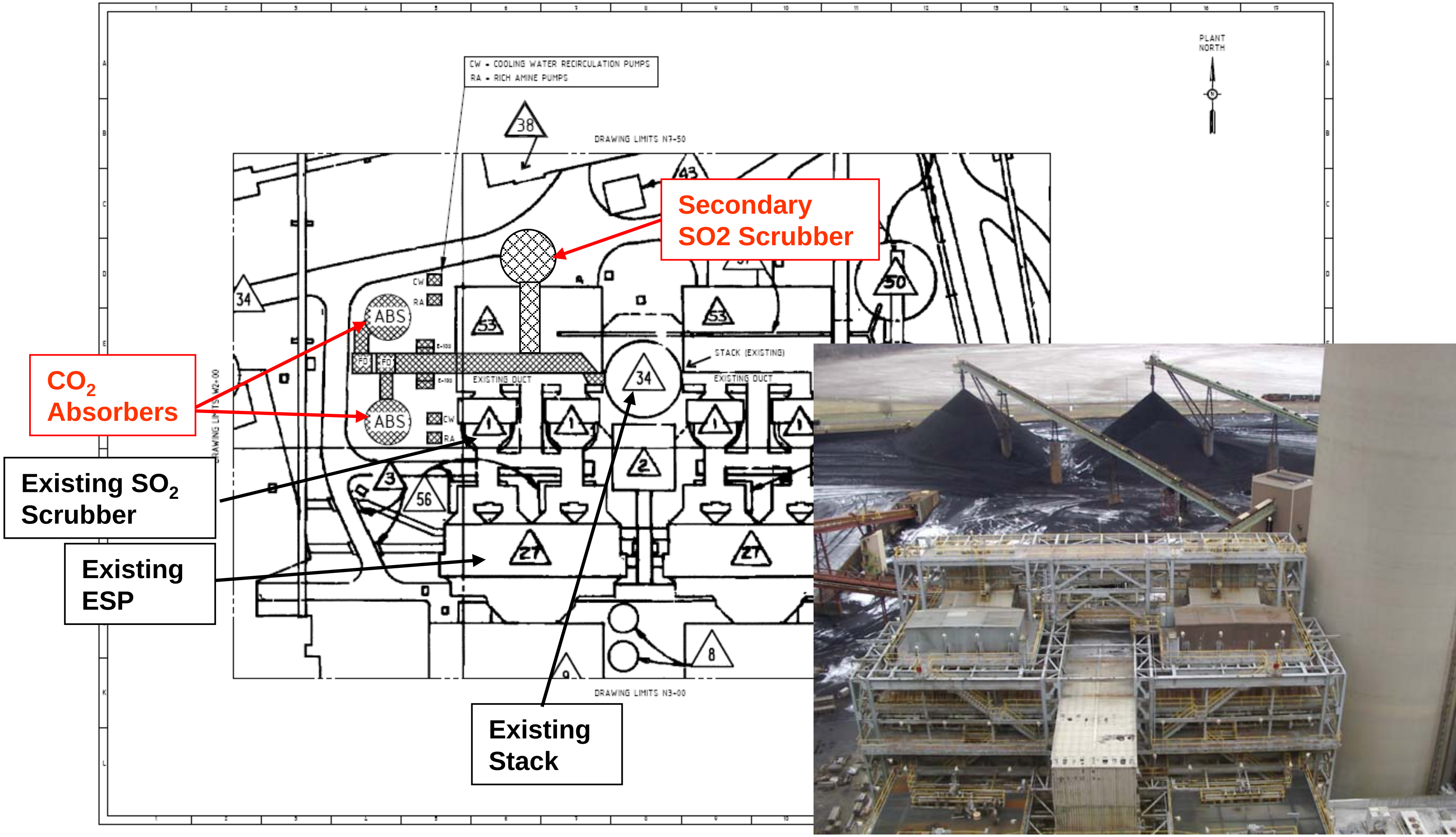


Potential solution by properly matching MEA plant requirements and retrofit design

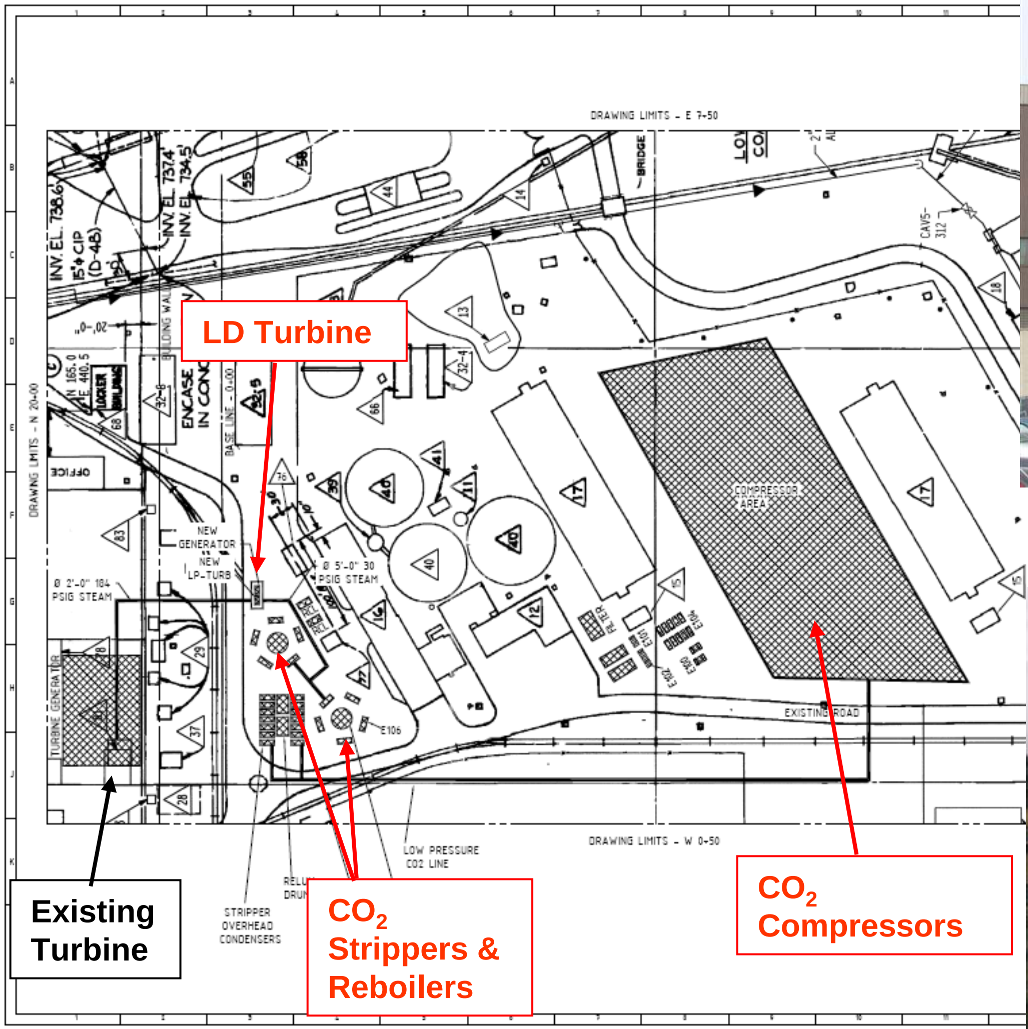
# New Equipment Locations Identified



# Plot Plan (Absorber location)



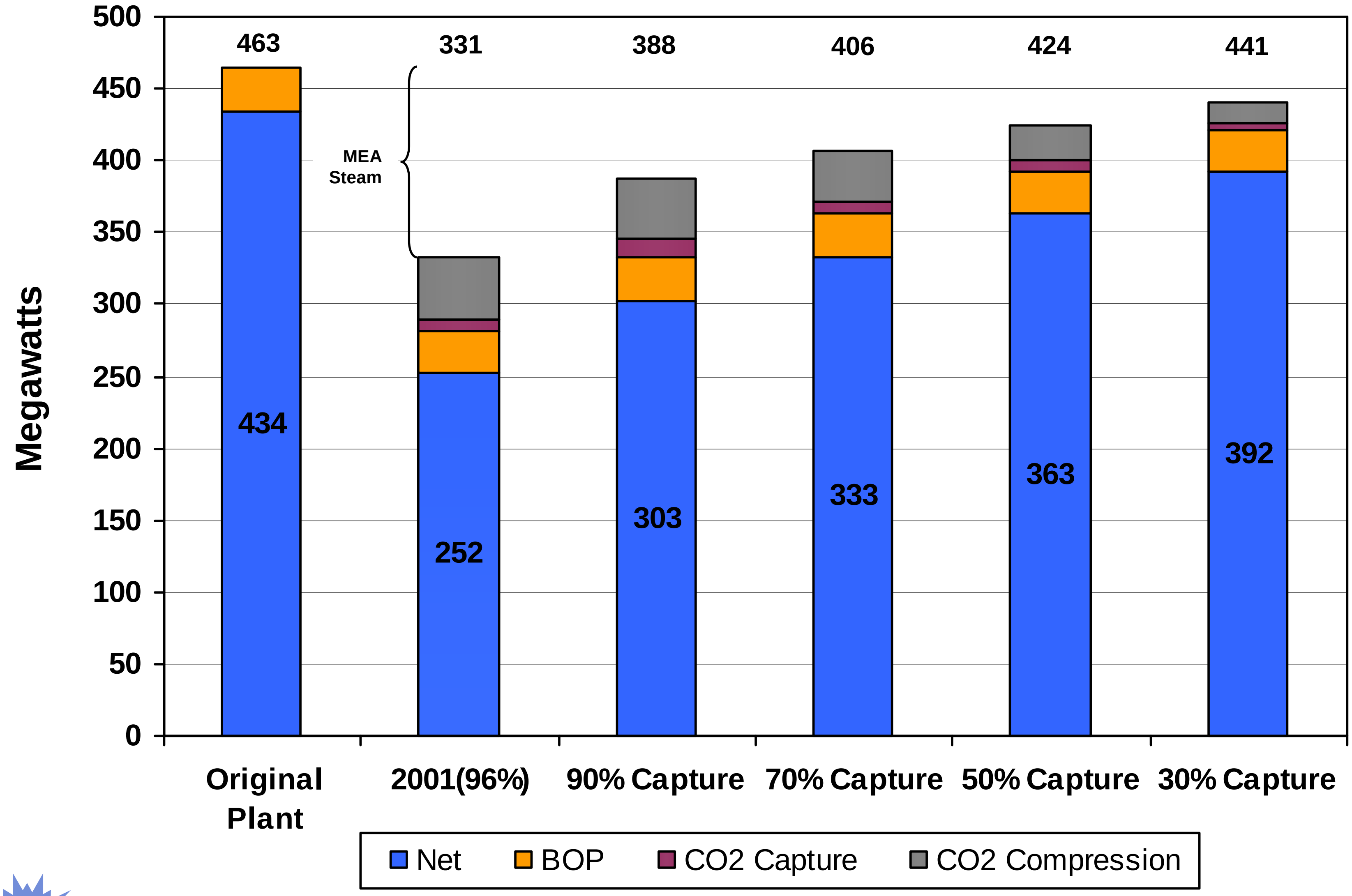
# Plot Plan – Let Down Turbine, Strippers, & $CO_2$ Compressors




# Plant Performance

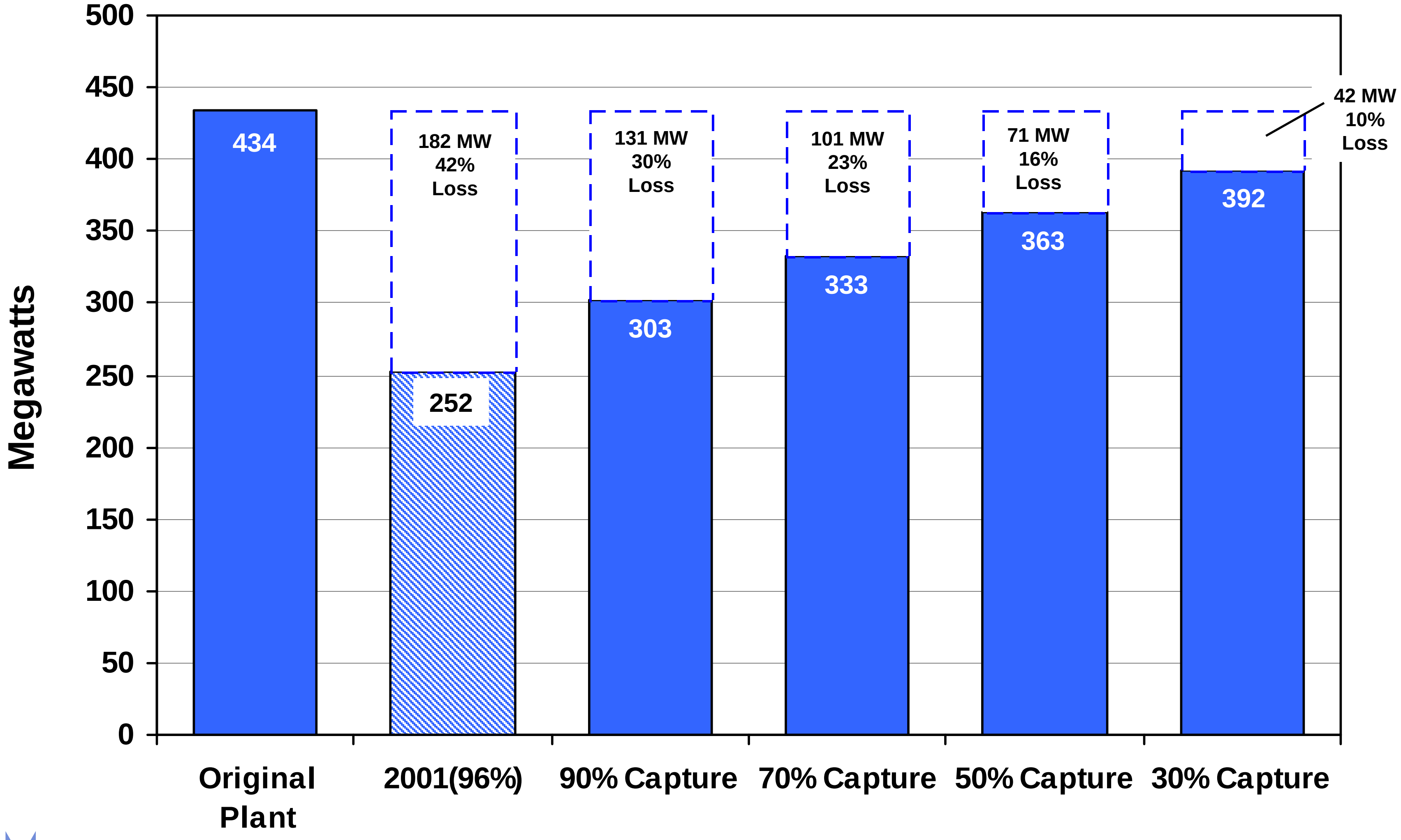
- Plant Electrical Output
- Plant Auxiliary Power
- Plant Thermal Efficiency
- Plant $CO_2$ Emissions

# Power Output Distribution

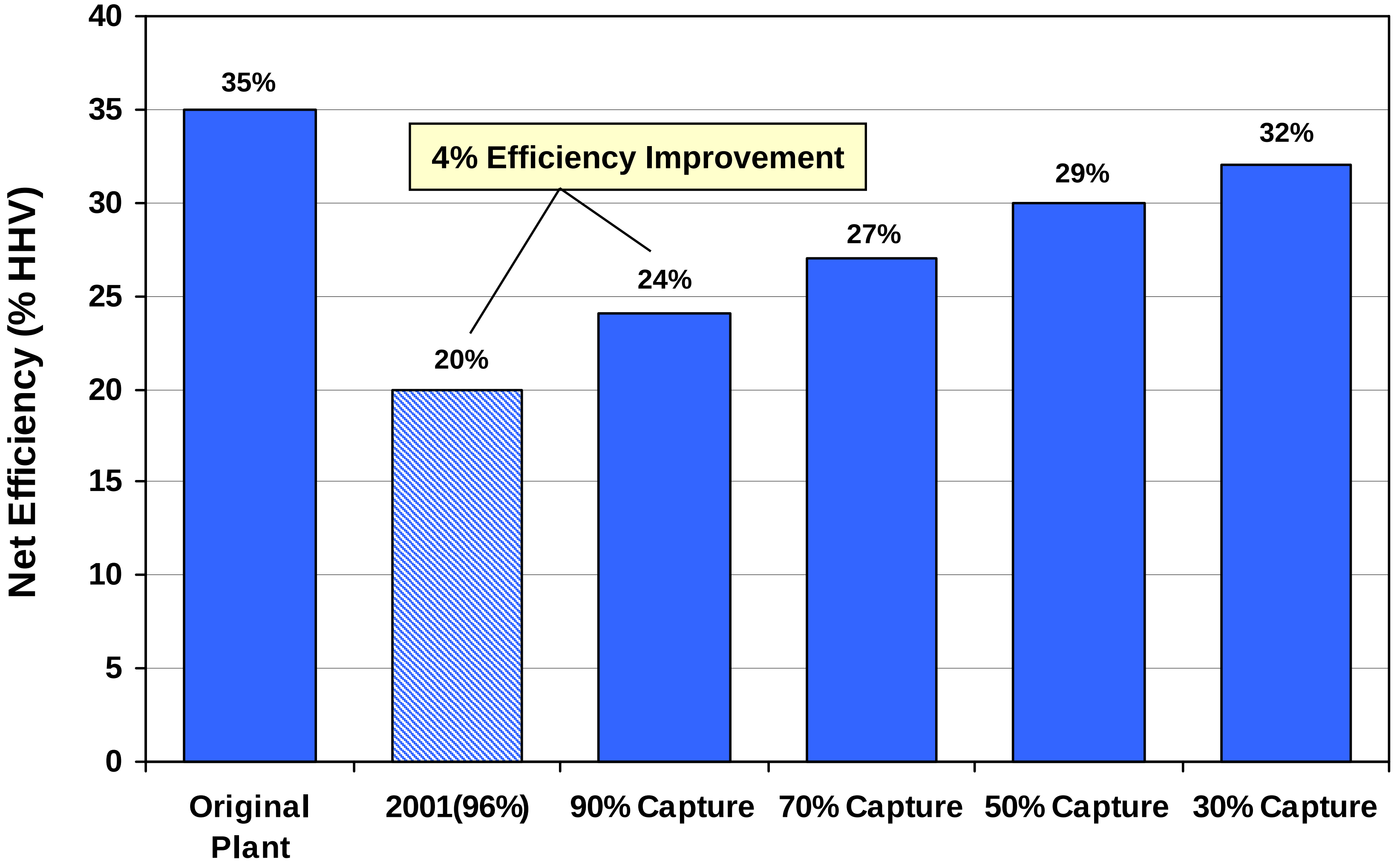


# Base load (Net) Output Impact

*Losses to Grid*



# Plant Thermal Efficiency
## *(HHV Basis)*



# Summary Performance Results

| | Base | 2001 | 2006 Study | | | |
|---|---|---|---|---|---|---|
| **% $CO_2$ Capture** | **0** | **96** | **90** | **70** | **50** | **30** |
| **Gross Power (MW)** | **463** | **331** | **388** | **406** | **424** | **441** |
| | | | | | | |
| Base Plant Load | 30 | 30 | 30 | 30 | 30 | 30 |
| Gas Cleanup/$CO_2$ Capture | - | 8 | 12 | 9 | 7 | 4 |
| $CO_2$ Compression | - | 42 | 43 | 34 | 23 | 14 |
| **Total Aux. Power (MW)** | **30** | **80** | **85** | **73** | **60** | **48** |
| Net Power (MW) | 433 | 251 | 303 | 333 | 363 | 392 |
| Heat Rate (Btu/kWh) | 9,749 | 16,875 | 13,984 | 12,719 | 11,670 | 10,796 |
| **Efficiency (HHV)** | **35** | **20** | **24** | **27** | **29** | **32** |
| **Energy Penalty[1]** | **-** | **15** | **11** | **8** | **6** | **3** |

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

**5% Efficiency Improvement**

**Note**: 12% Capture penalty for a new sub-critical plant with MEA Capture
8% Capture penalty for a new super-critical plant with MEA Capture

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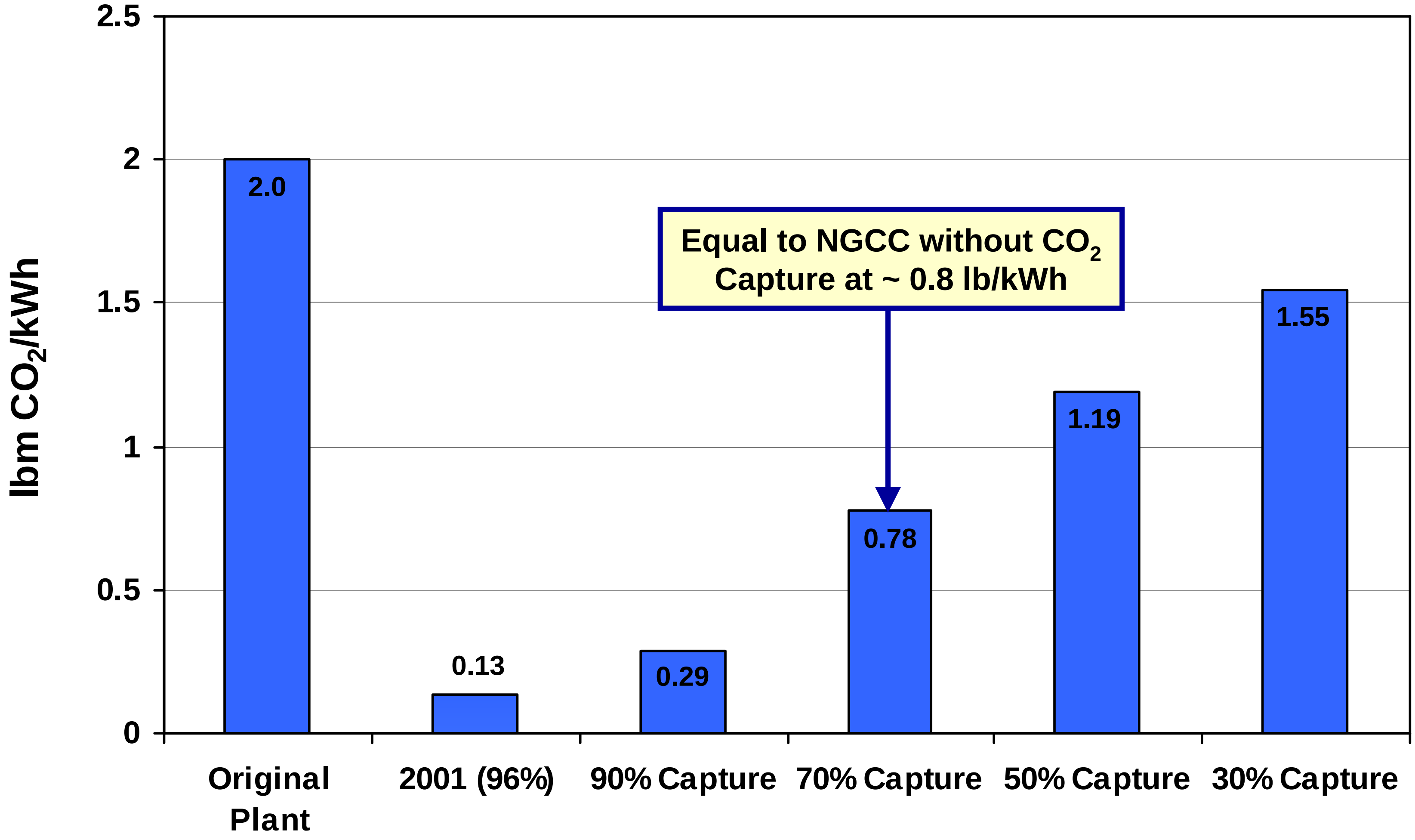
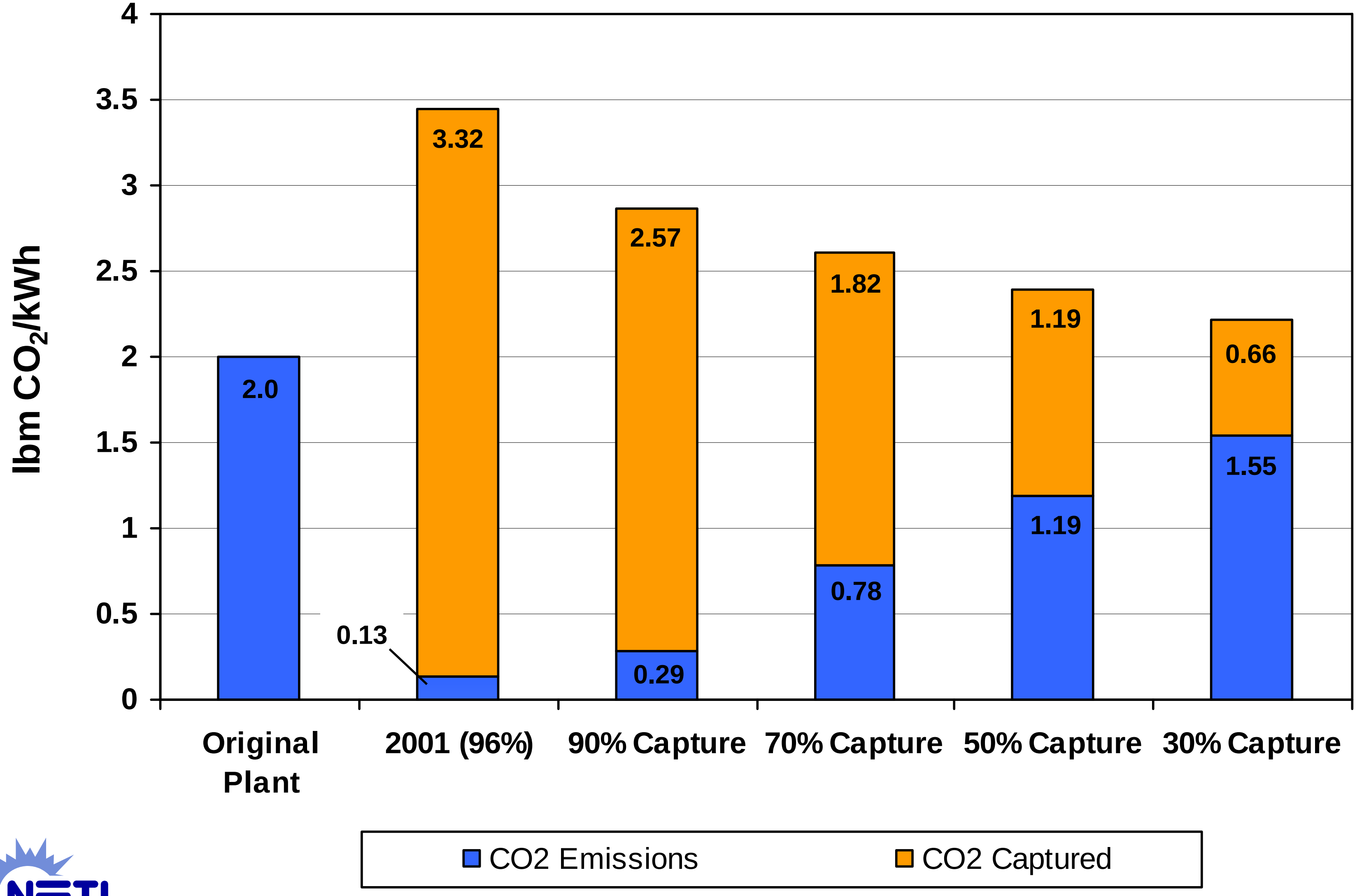
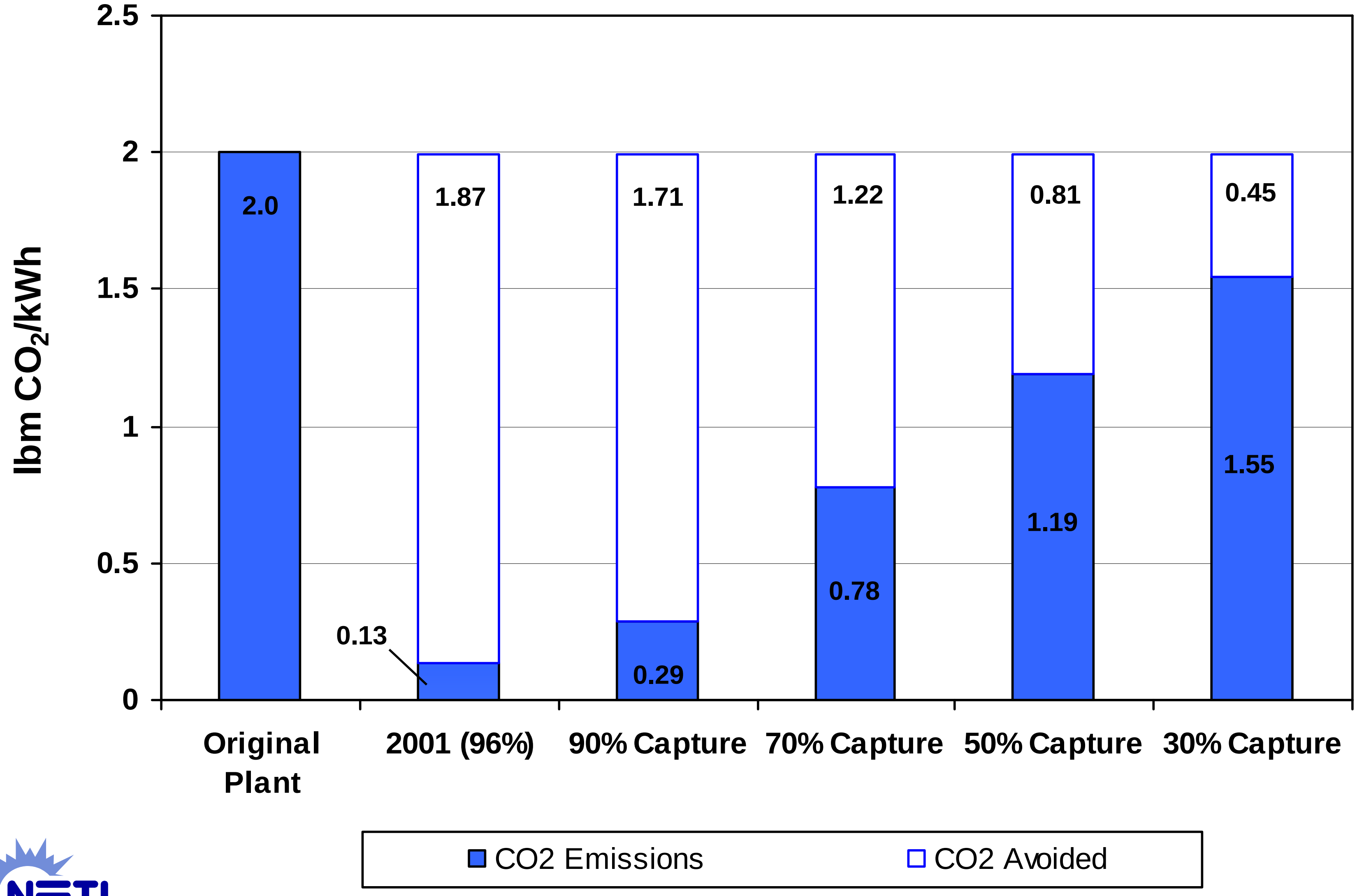
# $CO_2$ Emissions



# $CO_2$ Captured and Emitted



# $CO_2$ Avoided Emissions



# Economics

- Capital Costs
- Incremental COE
- Mitigation Costs
- Sensitivity Analyses

# Plant Retrofit Capital Costs

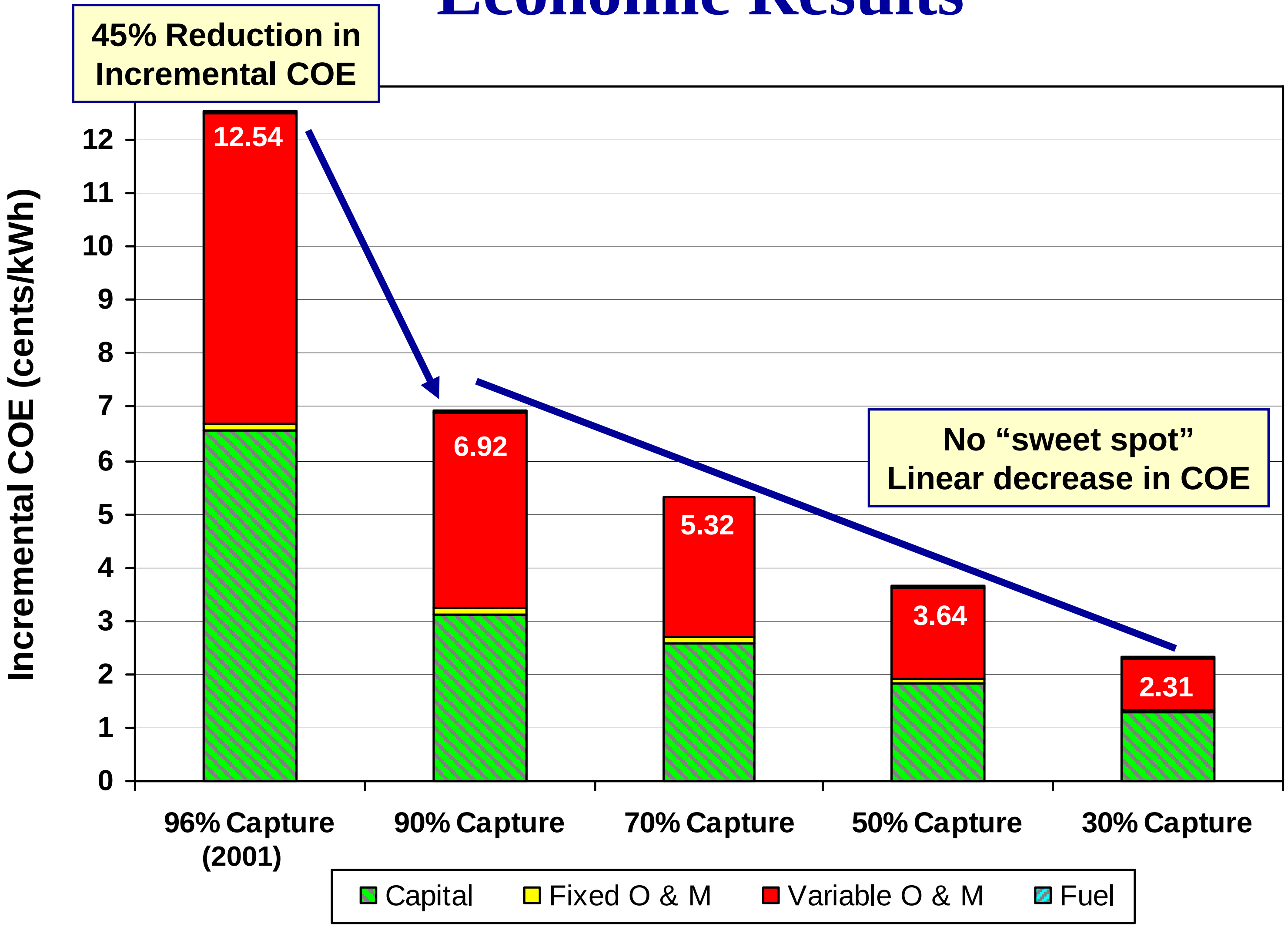
| EPC Costs ($1000's) | 2001 | 2007 Study | | | |
|---|---|---|---|---|---|
| % $CO_2$ Capture | 96 | 90 | 70 | 50 | 30 |
| $CO_2$ Capture & Compression | 668,277 | 368,029 | 333,406 | 249,490 | 181,070 |
| Flue Gas Desulfurization | 22,265 | 22,265 | 22,265 | 22,265 | 22,265 |
| Letdown Steam Turbine | 10,516 | 9,800 | 9,400 | 8,900 | 8,500 |
| Boiler Modifications | 0 | 0 | 0 | 0 | 0 |
| **Total Retrofit Costs** | **701,057** | **400,094** | **365,070** | **280,655** | **211,835** |
| | | | | | |
| New Net Output (kW) | 251,634 | 303,317 | 333,245 | 362,945 | 392,067 |
| **$/kW-New Net Output** | **2,786** | **1,319** | **1,095** | **773** | **540** |
| **$/kW-Original Net Output*** | **1,616** | **922** | **842** | **647** | **488** |

*Original net output = 433,778 kW

**53% Reduction in Incremental Capital Costs**

Note: Capital costs from 2001 study were escalated to July 2006 dollars

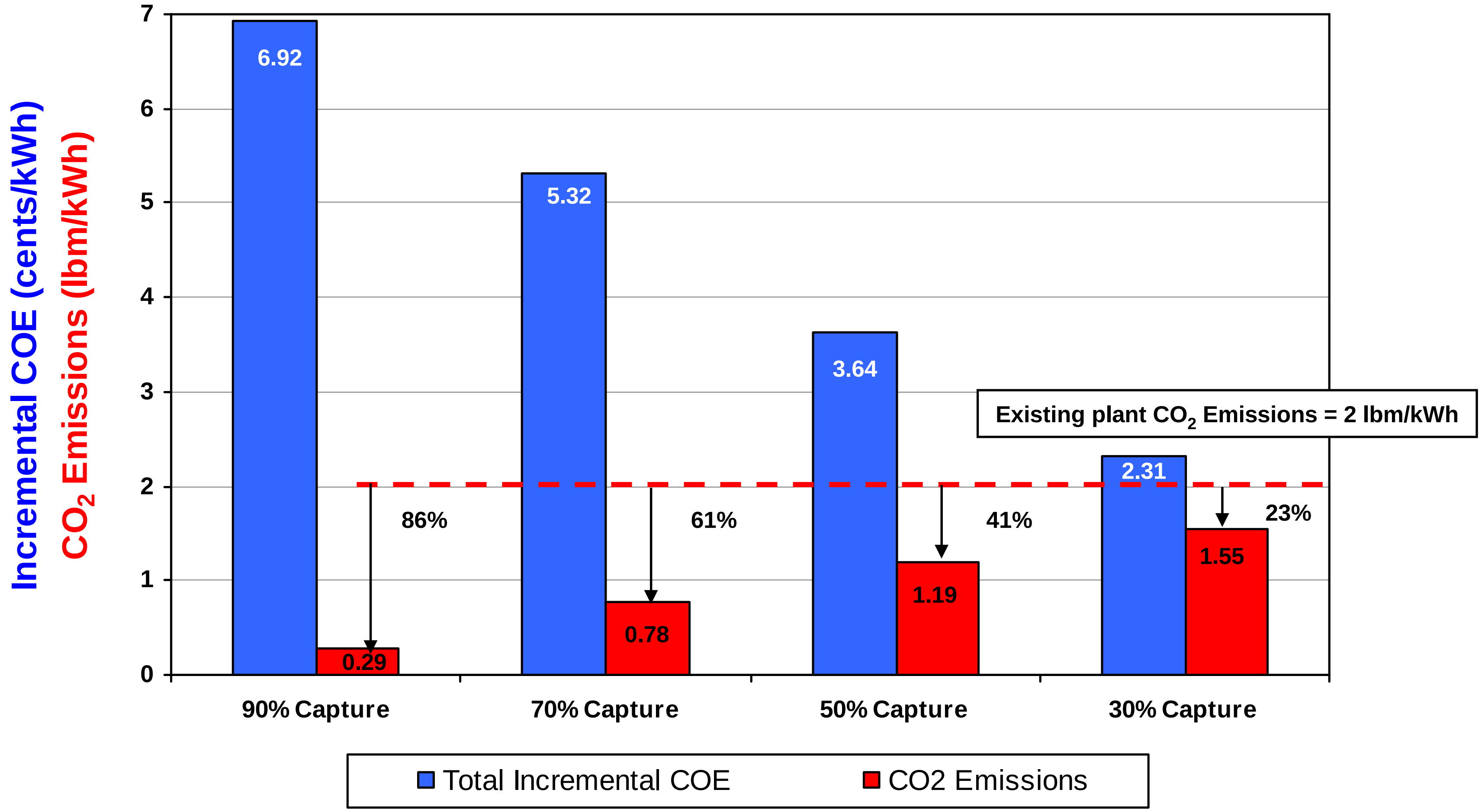
# Economic Results




**Note**:
Make-up power assessed at 6.40 ¢/kWh
Economic results from 2001 study were escalated to 2006 dollars
Variable O&M cost includes $SO_2$ Credit at $608/ton

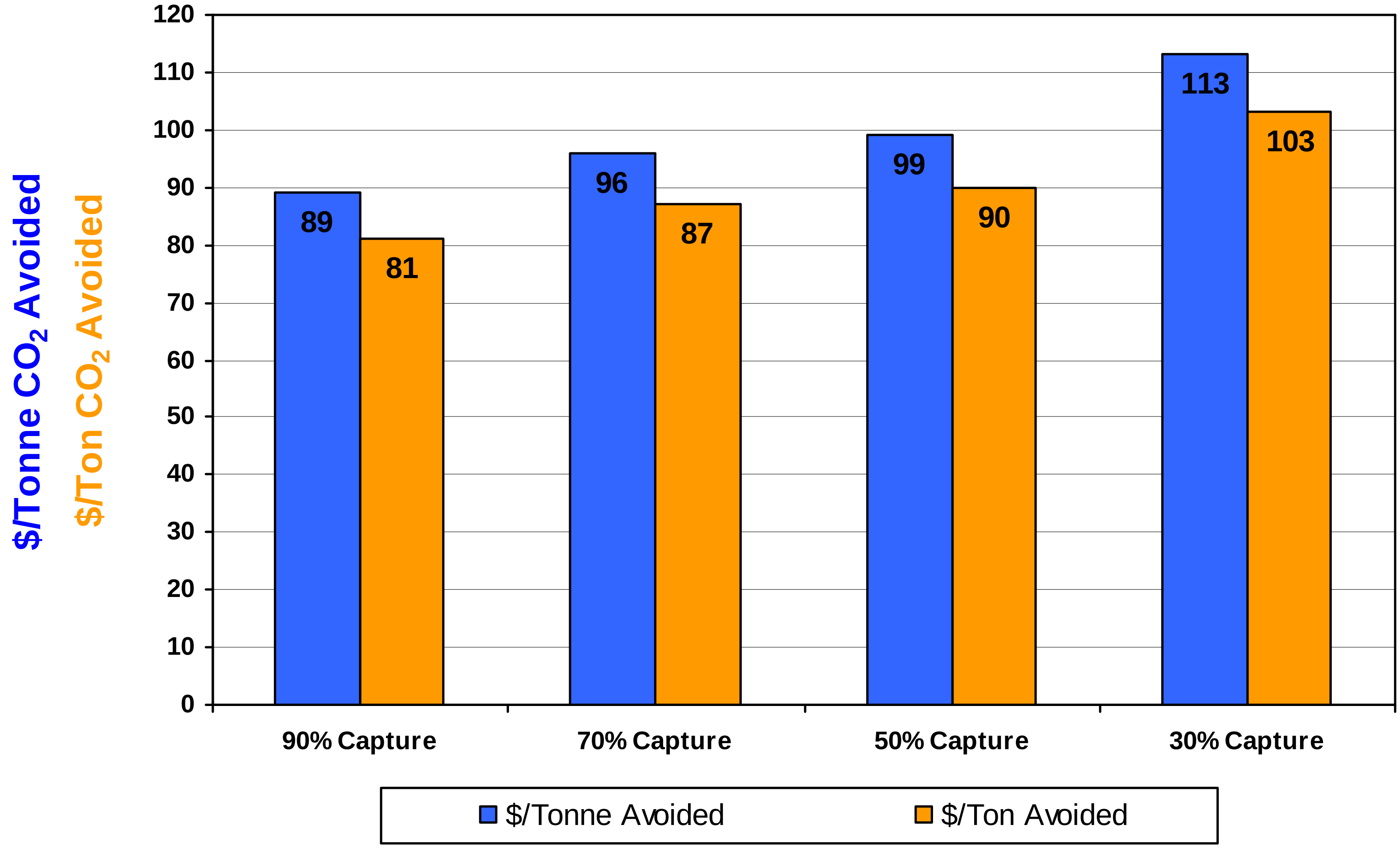
# Economic Results

## *Cost for Reducing Emissions*



# Economic Results

## *$CO_2$ Avoided Cost*

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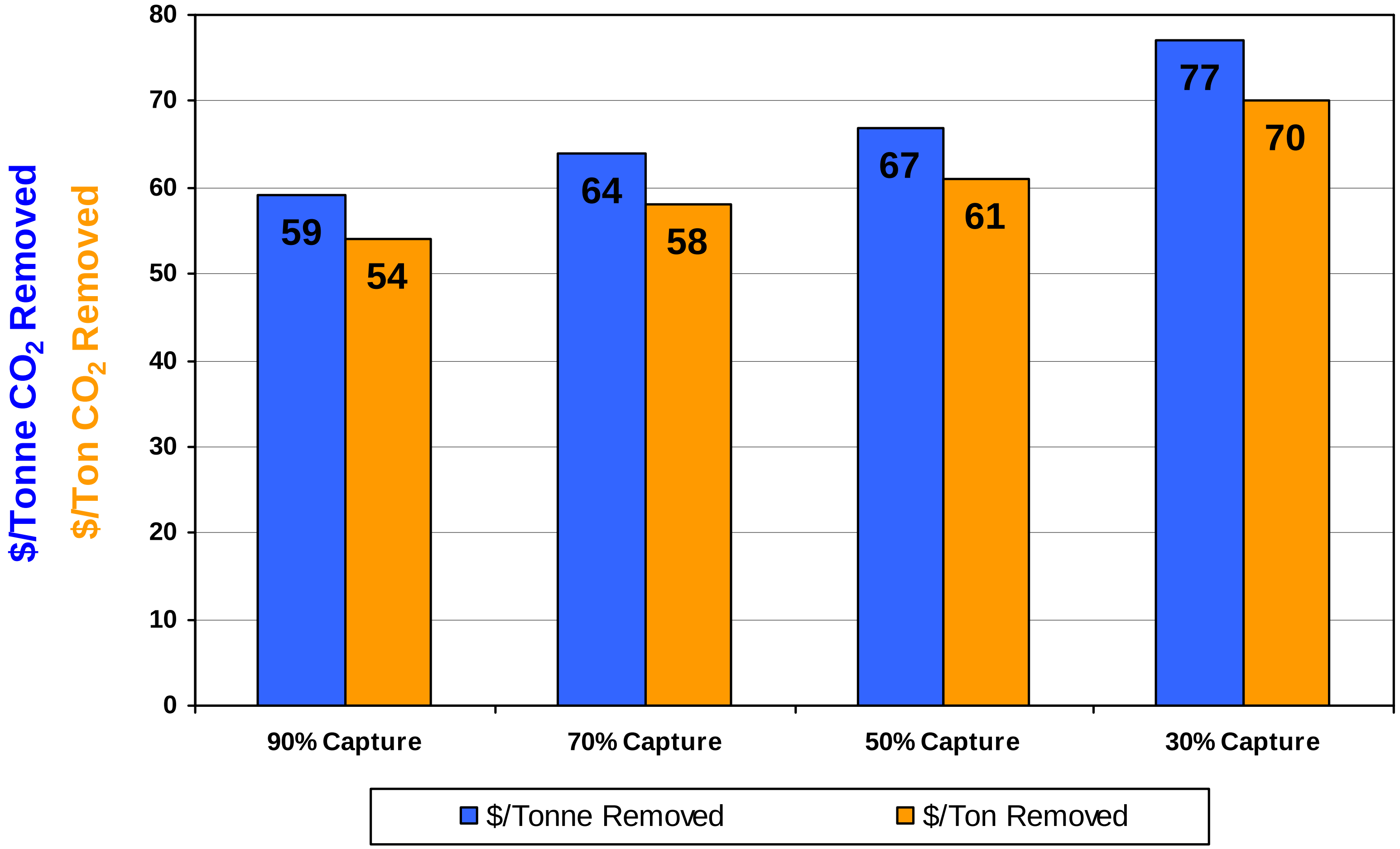
# Economic Results

## *$CO_2$ Captured Cost*



# Conclusions

1. **No major technical barriers found**
2. **Compared to the 2001 study, this study with an advanced amine (90% $CO_2$ Capture case) showed:**
   - **Marked improvement in energy penalty and reduction in cost**
3. **No Sweet Spot—near linear decrease in incremental COE with reduced $CO_2$ capture level**
4. **Sufficient results to answer various definitions of "optimal $CO_2$ capture" from existing plants**

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