the Energy to Lead

Natural Gas and Carbon Capture and Sequestration

Ron Edelstein
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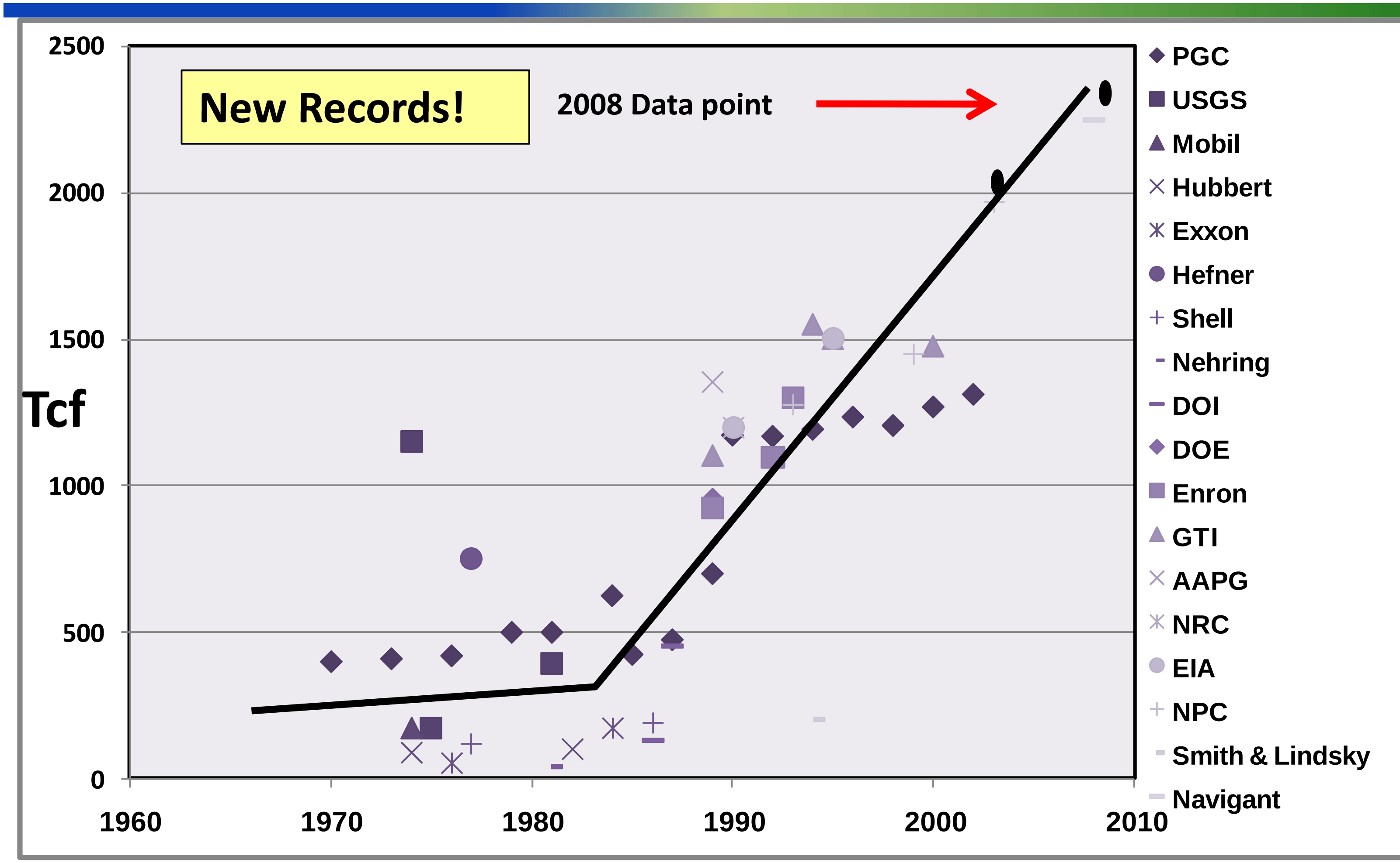
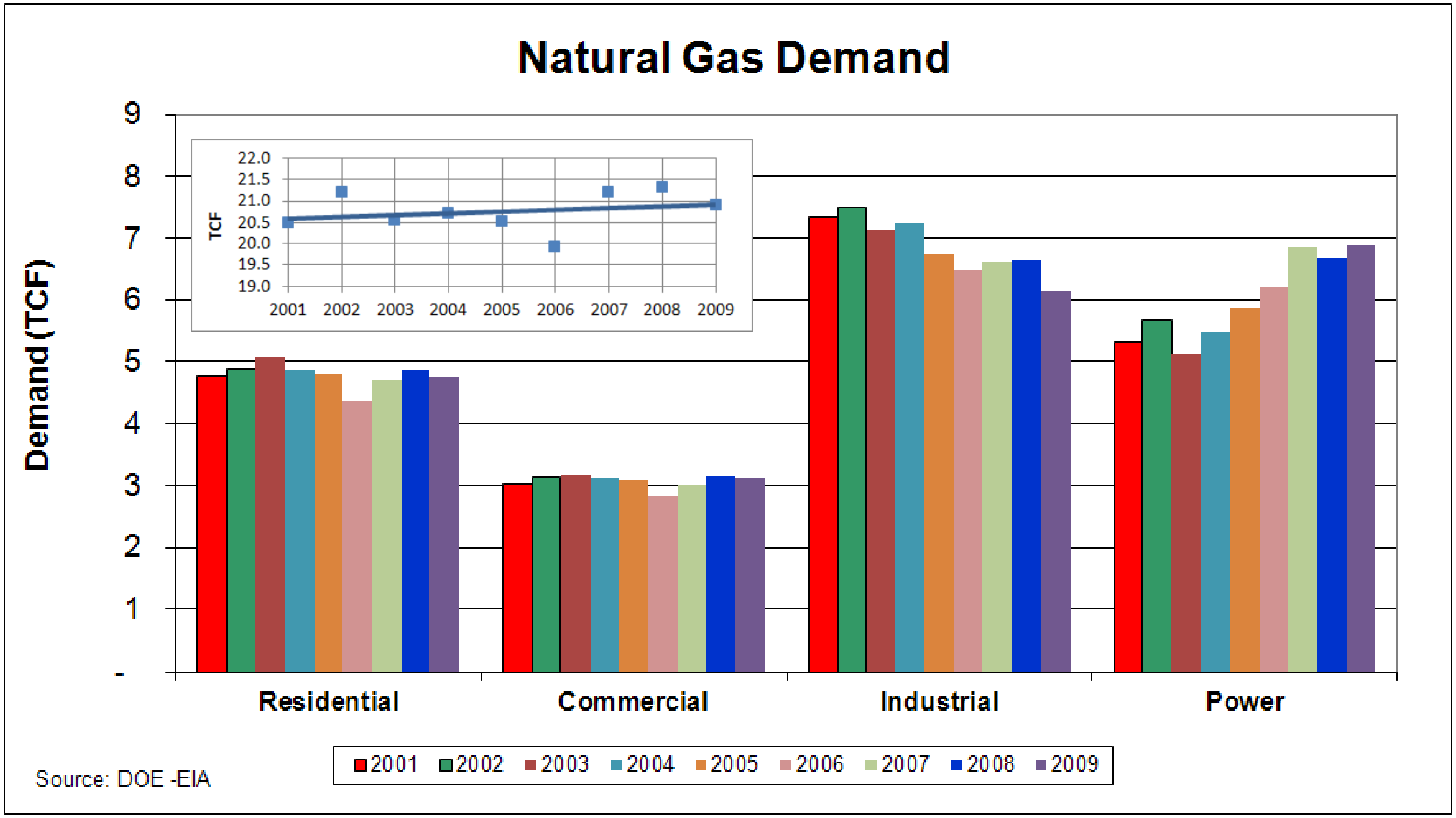
Key Issues

1. Natural gas use in power generation
2. Technical comparisons
3. Cost comparisons
4. Conclusions

U.S. Technically Recoverable Gas (Tcf)



Natural Gas Demand Trends



Total demand up slightly – driven by power generation.

Signs of modest industrial rebound in 2010 – and continued power gen demand.

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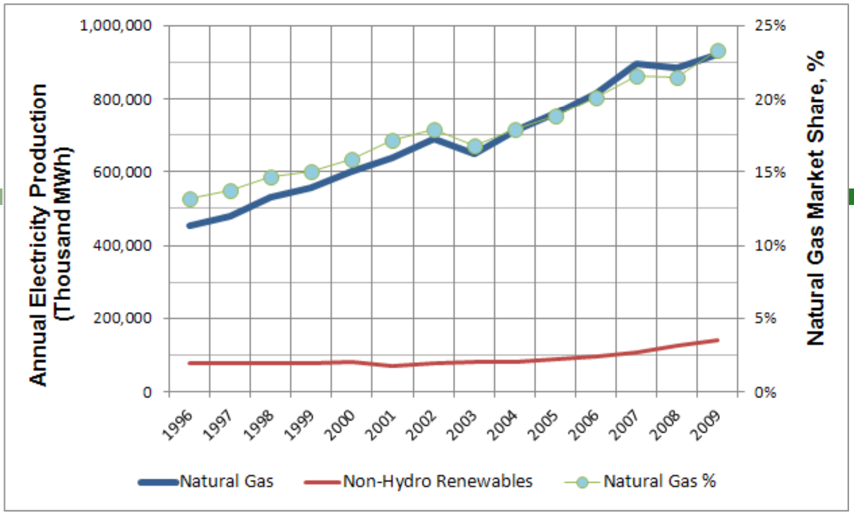
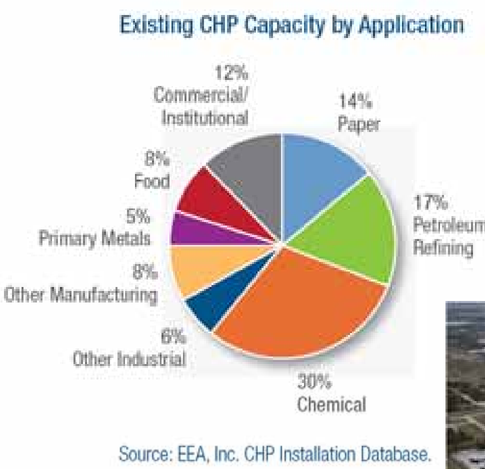
US Power Generation Market

> Growing role for natural gas and renewables
  – High-efficiency **gas turbine combined-cycle** plants
    > Low-carbon option with CCS
  – Complemented by **combined heat and power** (CHP) system
  – Gas **enables renewables**
    > Fast response grid support for intermittent generators (solar, wind
    > Supplemental heat for solar therma power plants
    > Natural gas boost for bio-methane BTU content; pipeline infrastructure for delivery



US Power Production
Steady natural gas growth from 13% in 1996 to current 23% in 2009



FPL Hybrid Solar Thermal and Gas Turbine Power Plant

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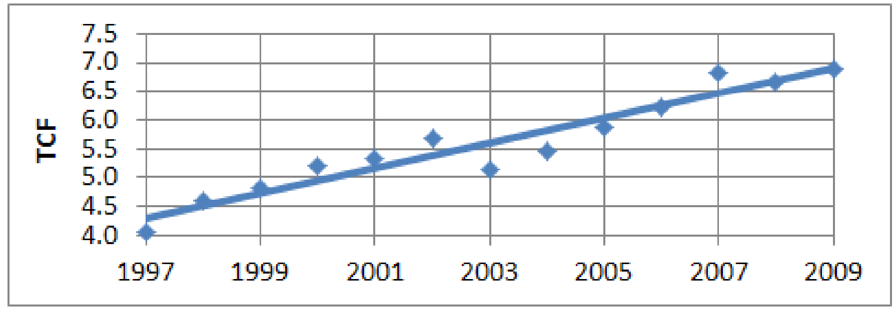
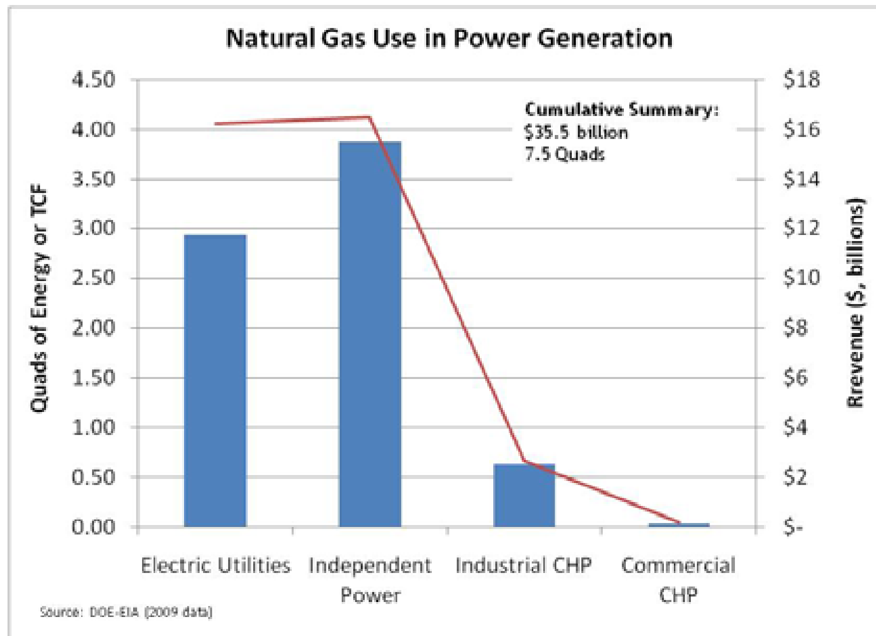
EIA Data from 2010 Annual Energy Outlook

- Electricity demand increases by 30% by 2035
- Natural gas generation remains at 21%
- Most new capacity additions use natural gas or renewables
  - 250 GW needed between now and 2035
  - Natural gas plants account for 46% of additions
  - Renewables account for 37%

Natural Gas Use in Power Generation

- Power generation key growth market for natural gas in past decade
- Confluence of factors likely to continue trend (possibly accelerate)
  - Aging coal plants
  - Tight coal power margins with low natural gas prices
  - Increasing pressure on various environmental emissions (NOx, SO2, mercury, CO_2)





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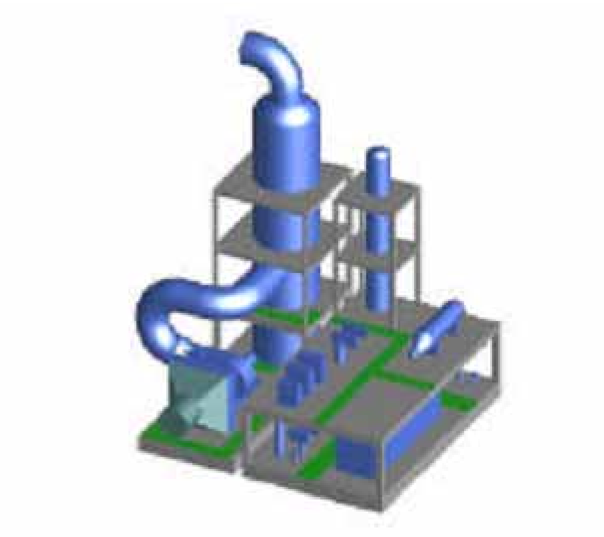
Natural Gas and CCS: The Good News and the Bad News

- Natural gas combined cycle plants have efficiencies of over 50%, compared to around 30-35% for coal power plants
- Natural gas, when combusted, released only 117 lb of CO_2/MMBtu, compared to 207 lb/MMBtu for coal
- Overall effect is to lower CO_2 output/kWhr to less than half of that for coal plants
- But…this lower the CO_2 percentage in the exhaust gas, making concentration of the CO_2 more challenging

Integral Membrane/ Absorption Process Leads to CapEx & OpEx Savings



Conventional Amine Scrubber Column

Carbo-Lock™ Membrane Contactor

Membrane Advantages:

- **Capital Cost (CapEx) 35%**
- **Operating Costs (OpEx) 40%**
- Dry Equipment Weight 35%
- Operating Equipment Weight 37%
- Total Operating Weight 47%
- Footprint Requirement 40%
- Height Requirement 60%

*Data by Aker Kvaerner

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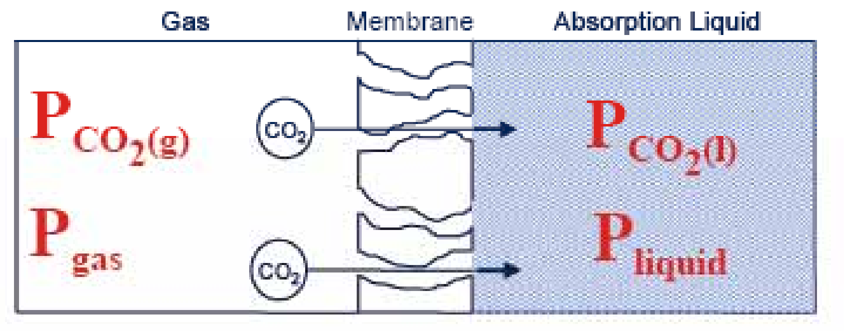
Basic Principles of Carbo-Lock™ Contactor

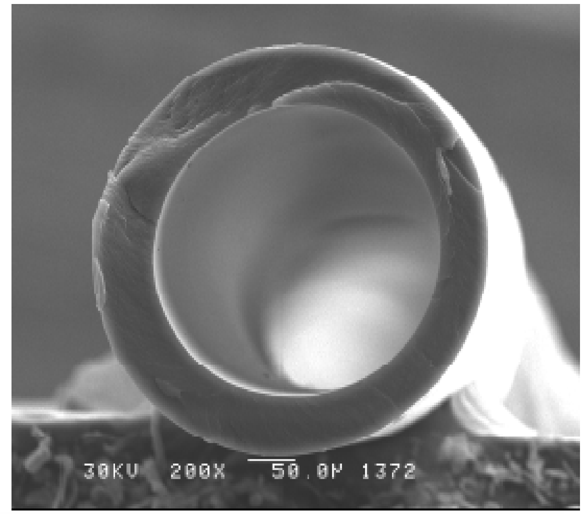
Membrane mass transfer principle

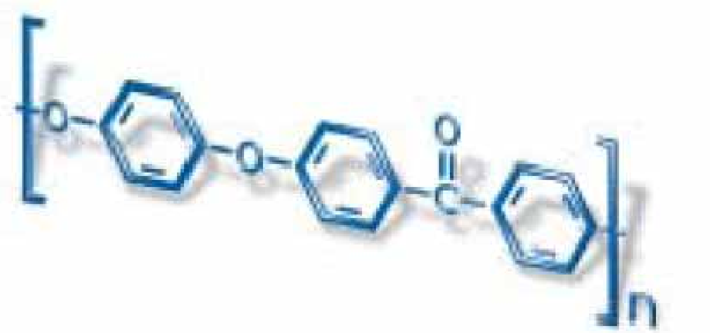


- Porous, hollow fiber membrane
- Unique membrane material , PEEK
- Membrane matrix filled with gas
- Mass transfer by diffusion reaction
- Driving force: difference in partial pressures of component to be removed/absorbed (PCO_2(g)>PCO_2(l))
- Liquid on one side, gas on the other side of the membrane
- Pressure difference between shell and tube side can be almost zero
- ($P_l \geq P_g$), i.e. the mass transfer is not pressure driven

Membrane Material Properties of PEEK

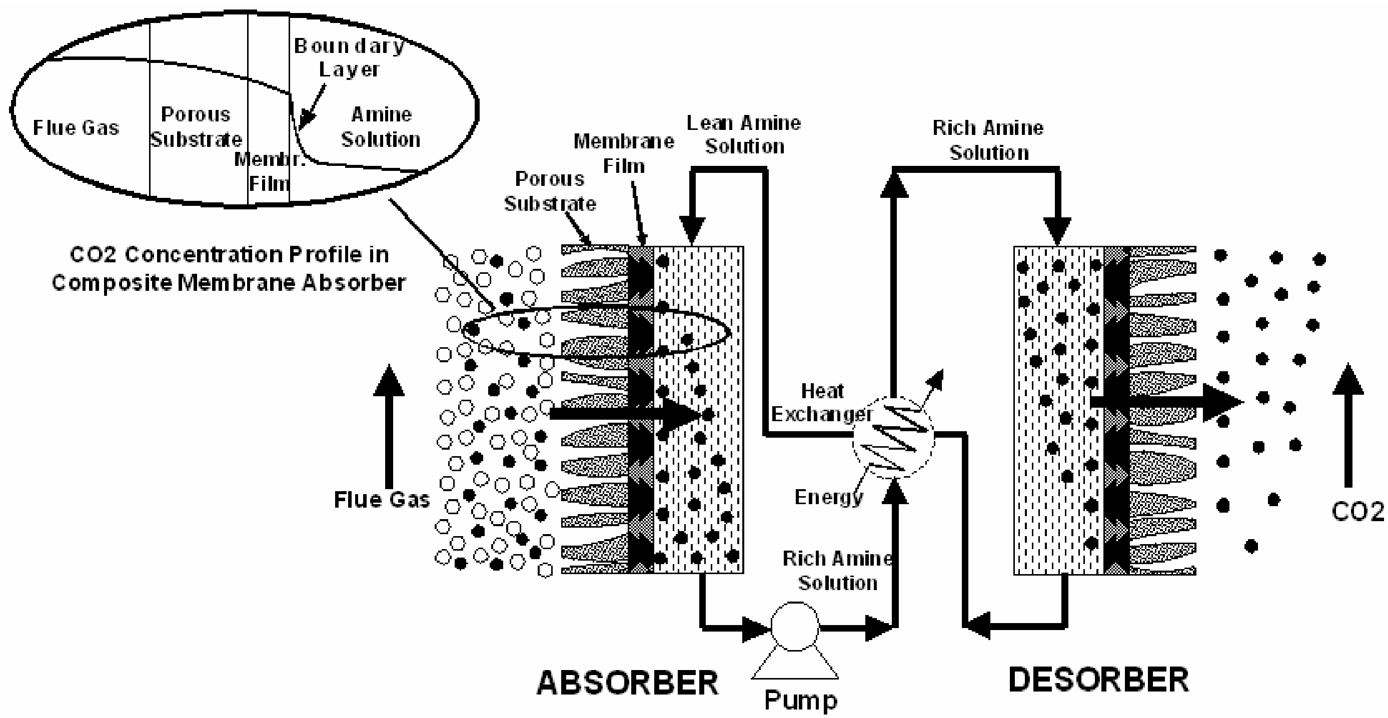
- Very high heat resistance – operate to 200^{+} C
- High rigidity
- High dimensional stability
- Good strength
- Excellent sliding friction behavior, minimal abrasion
- Excellent chemical resistance
- Excellent hydrolytic stability
- Average pore size 5 to 50 nm
- Average porosity 40 to 70%
- 800 psi water breakthrough pressure





PEEK can operate continuously in contact with aggressive amine solvents

CO_2 Recovery with Carbo-Lock™ Process Replaces Amine Columns with Membrane Contactors



Integral Membrane Absorption Process for CO2 Capture from Flue Gas

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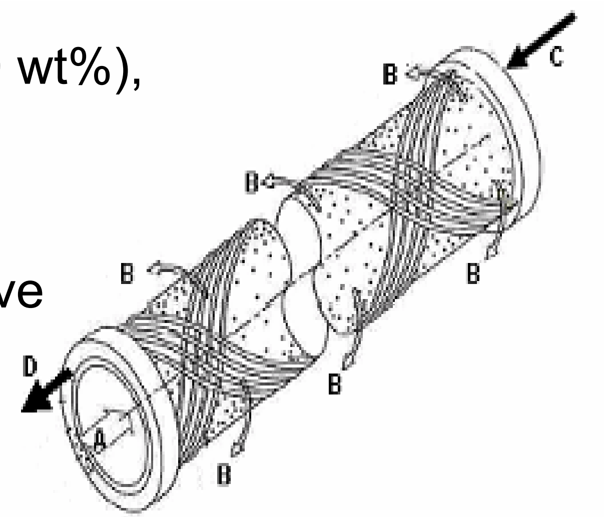
Essentially All CO_2 Absorbents are Compatible with Carbo-Lock™ Process

- Primary Amines MEA (25 wt%)
- Secondary Amines DEA (35 wt%), DIPA (40 wt%), DGA (40 wt%)
- Tertiary Amines TEA (40 wt%), , MDEA (40 wt%),
- Hindered Amines 2-AMP (40 wt%), 2- iPrAMP (40 wt%),
- 30 wt% 2-BAE / 3 wt% 2-MP
- Mixed Amines 40 wt% MDEA / 6 wt% MEA
- Hot Potassium Carbonate 30 wt% Inactive or active w/ DEA, AMP
- Ionic Liquids
- Cold Ammonia
- Selexol

Amine concentration in solvent (typically water)



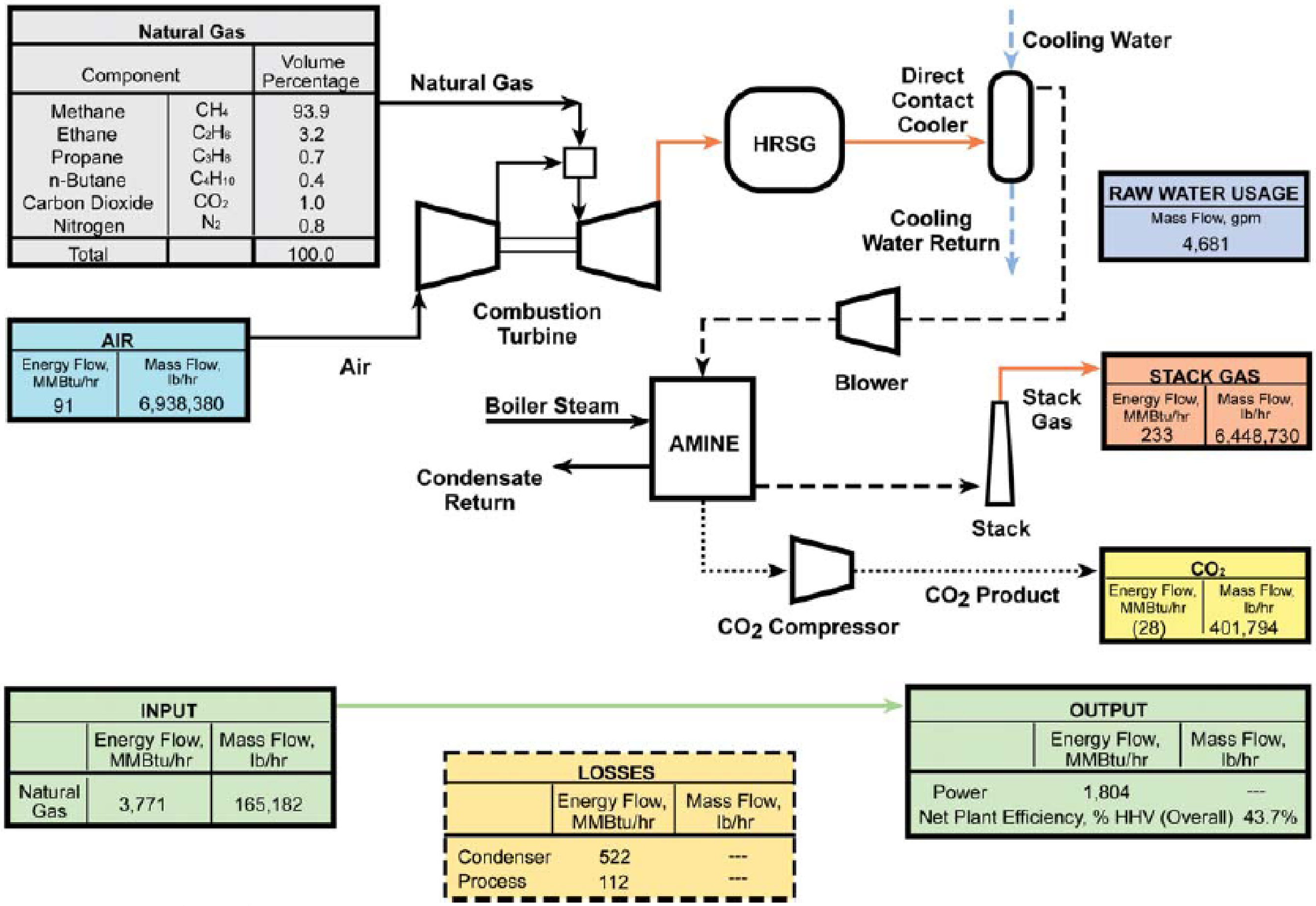
Hollow fiber membrane contactor for purification of flue gas (A: lean solvent; B: rich solvent; C: CO_2-rich feed flue gas; D: CO_2 lean flue gas)

Previous Membrane Contactor Work – Natural Gas CO_2 Treatment and Dehydration

Lab-, bench- and field-scale gas/liquid membrane contactor unit

- **4.5 MMscfd**
- **22 gpm**
- **1290 psig**

DOE Cost & Performance Comparison of Fossil Power Plants



DOE/NETL-2007/1281 (2007)

GTI Model Predicts Higher Plant Efficiency and Lower COE with Carbo-Lock™

Basis	DOE		IECM
	Case 13	Case 14	Capture
CO_2 Capture Technology	No	Conv. Column	**Membrane CarboLock**
Gross Power Output (kW_e)	570,200	520,900	516,840
Auxilary Power Requirement (kW_e)	9,840	38,200	55,000
Net Power Output (kW_e)	560,360	481,890	461,900
Natural Gas Flowrate (lb/h)	165,182	165,182	148,740
Net Plant HHV Efficiency (%)	50.8	43.7	45.73
Net Plant HHV Heat Rate (Btu/kW-h)	6,719	7,813	7,461
Total Plant Cost ($x1000)	310,710	564,628	449,800
Total Plant Cost ($/kW)	554	1,172	974
LCOE (cents/kWh)	6.9	9.7	8.8
CO_2 Avoided Costs ($/tonne)	N.A.	92	59

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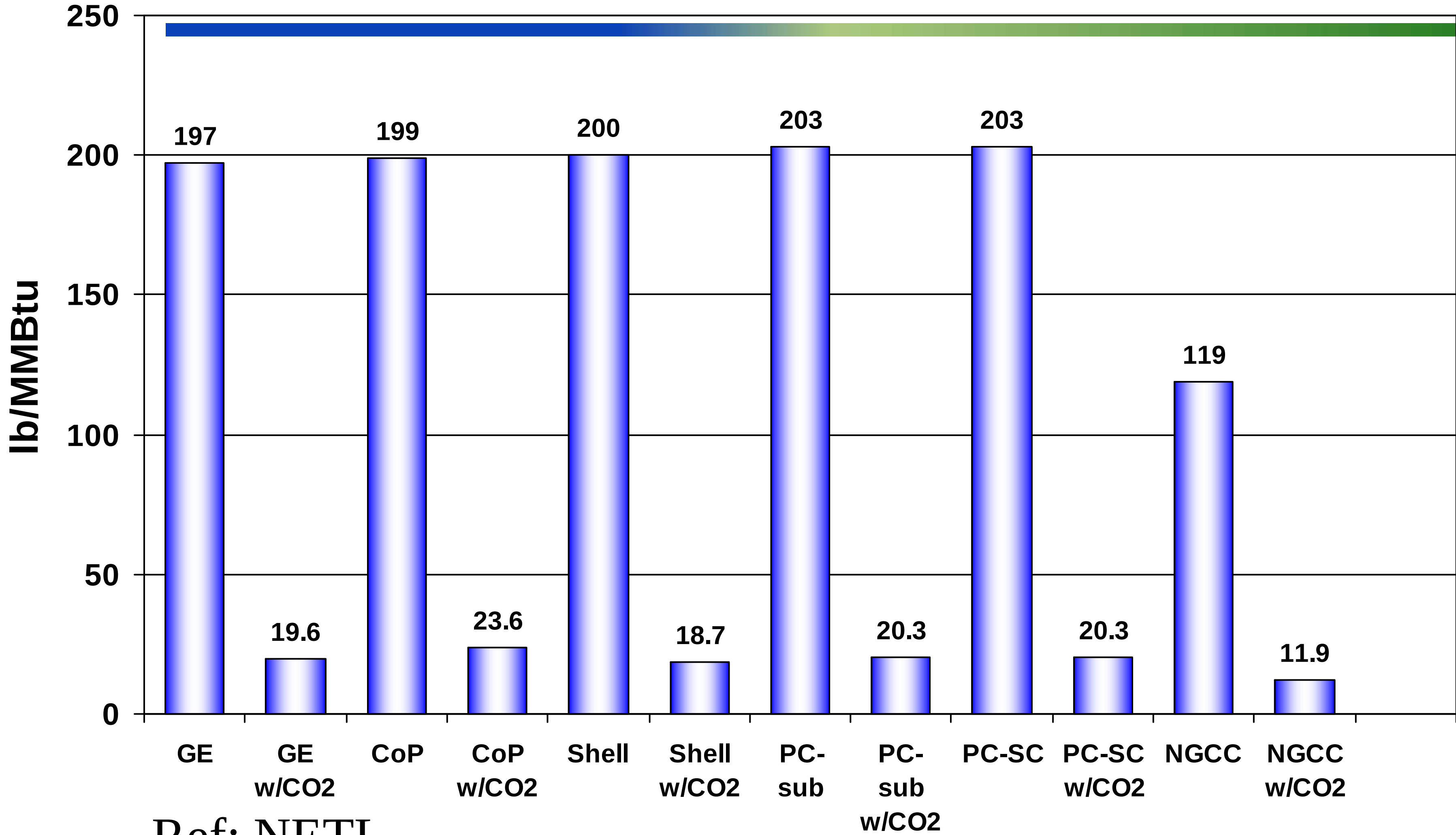
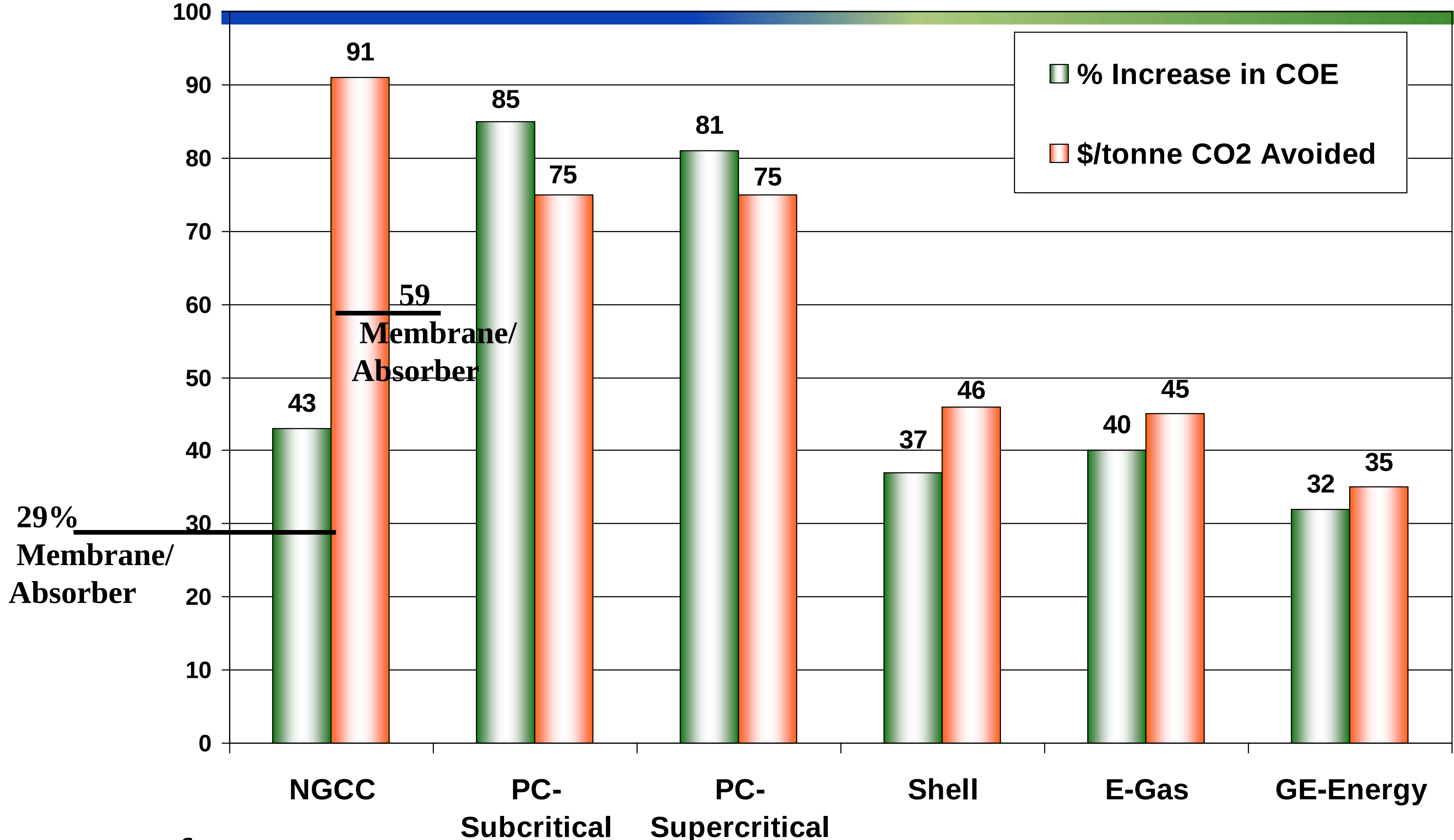
NETL Study: CO_2 Emissions for All Cases



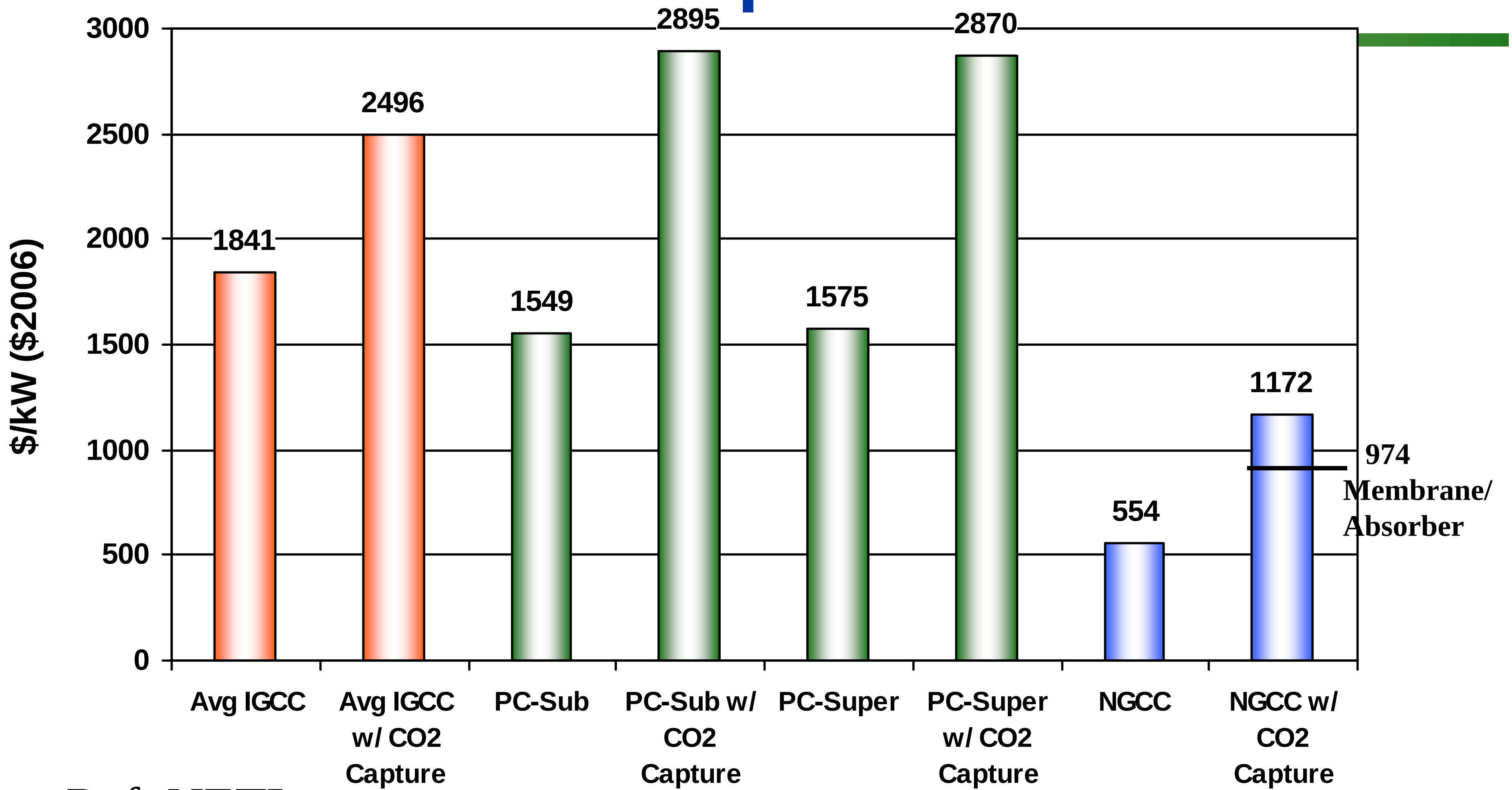
Ref: NETL

NETL Study Modified: CO_2 Mitigation Costs



Ref: NETL

NETL Study Modified: Total Plant Cost Comparison



Ref: NETL

Total Plant Capital Cost includes contingencies and engineering fees

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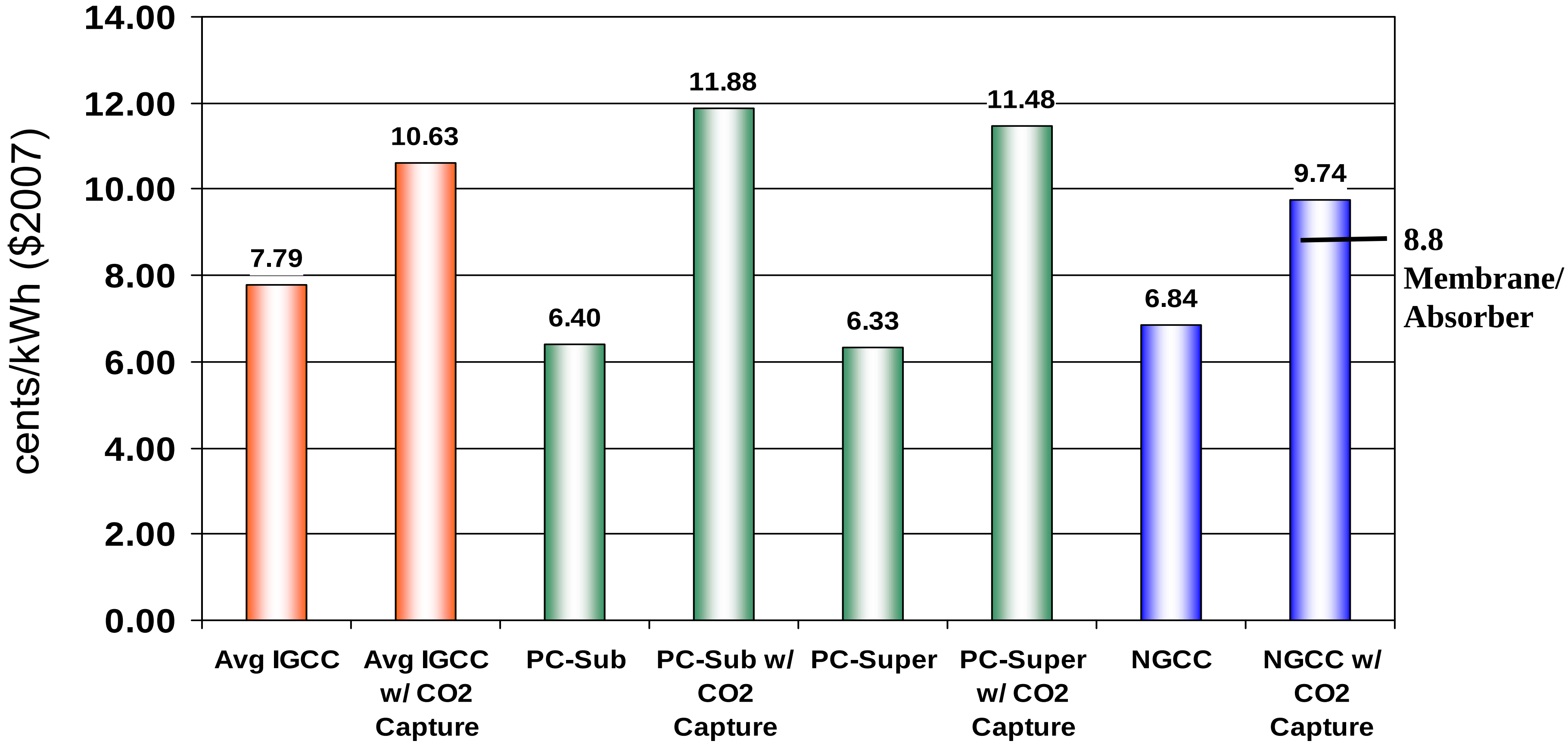
NETL Study Modified: Cost of Electricity Comparison



January 2007 Dollars, Coal cost $1.80/10^6Btu. Gas cost $6.75/10^6Btu

Ref: NETL Study modified with GTI Membrane Unit

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Potential Opportunity – RD&D for NGCC Applications

> Phase 1 – Proposed

- Task 1 – Lab-scale Testing of Membrane Contactor and Contactor Preparation
  - Objective: Membrane optimization and obtain basic operating parameters, prepare membranes for prototype-scale testing
- Task 2 – Prototype-scale Field Testing of Membrane Contactor
  - Objective: Process validation and performance testing with realistic feed
- Task 3 – Engineering and Economics
  - Objective: Engineering components, integration into NGCC power plant, economic impact of technology on COE

> Phase 2 – Future

- Task 4 – Demonstration-scale Field Testing of Membrane Contactor
  - Objective: Scale-up testing to obtain engineering parameters for design of full-scale units

Summary

- Natural Gas CCT with CCS and Carbo-Lock:
  - Lower first costs
  - Lower Cost of Energy with gas below $7.00/MMBtu
  - $/tonne of CO_2 removed costs competitive with PC plants,
    - Slightly higher than IGCC due to lower CO_2-producing fuel
- Other alternatives
  - Energy efficiency
  - Direct gas use
  - Renewables
  - CHP