$CO_2$ Capture Systems and Opportunities for Process Intensification

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Timeline of Carbon Capture Research

1992
First International Conference on Carbon Dioxide Removal (ICCDR-1)

1993
DOE/MIT prioritize research needs for CO₂ capture and sequestration; first gen capture tech for PCC is aqueous amines

1997
NETL Carbon Capture Storage Program initiated with $1mil

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2000
DOE/NETL initiate Regional Carbon Sequestration Partnership (RCSP)

2003
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2007
10 year anniversary of CCS program, which has grown to $100M

2009
NETL announces 12 large-scale capture projects; First National Carbon Capture Center (NCCC) opens led by DOE/NETL and Southern Company Services

2010
DOE/NETL publishes Carbon Dioxide Capture and Storage RD&D Roadmap

2011
DOE/NETL publishes Carbon Dioxide Capture and Storage RD&D Roadmap

2012
$80-100/ton CO₂
Breakthrough CCS project at Air Products and Chemicals begins capturing CO₂ and sending to oilfield for EOR; Initial release of CCSI Toolset

2014
Sask Power’s Boundary Dam commissioned

2015
2015
$60/ton CO₂

2016
2016
$60/ton CO₂

2017
2017
Petra Nova carbon emissions reduction system begins operation

2020
2020
$45/ton CO₂
Large scale pilot testing (10-25 Mwe) for 2nd gen tech

2025: 2nd gen tech target $40/ton CO₂

2030: Transformational tech target $30/ton CO₂
Need for CO₂ Capture

- CCS achieves 20% of cumulative reductions from 2015 to 2050 (storing over 123 Gt)

- International Target Compared to business as usual, assumes 66% less fossil fuel use, ~80% less coal use

+6 °C

Business as usual
+88% from 2009 to 2050

Emission Technology

- End-use fuel and electricity efficiency: 31%
- Renewables: 29%
- Carbon capture and storage: 20%
- End-use fuel switching: 9%
- Nuclear: 8%
- Power generation efficiency and fuel switching: 3%

International target
-50% from 2009 to 2050

CO₂


- Limits to efficiency gains, fuel switching reductions and CCS only option for some industrial sectors

- Delaying or abandoning CCS would increase power sector compliance cost by 40+%

Dispatchable Power with Capture Lowers Costs

“Firm low-carbon” resources like CCS and nuclear lower the cost of deep decarbonization by 10-62%
Cost Variability for Technology & CO₂ Concentration

Supercritical Pulverized Coal Power Plant

Conventional Coal with CO₂ Capture

Note: Block Flow Diagram is not intended to represent a complete material balance. Only major process streams and equipment are shown.
Supercritical Pulverized Coal Power Plant

- **Pre-treatment**
  - Lowers SO\(_x\) to ~ 1 ppmv from ~40 ppmv out of FGD

- **Cansolv CO\(_2\) Capture Process Details**
  - 90 % CO\(_2\) capture
  - Steam extraction from crossover pipe between IP and LP sections of steam turbine
  - Product CO\(_2\) ~ 30 psia

- **CO\(_2\) Compression System**
  - CO\(_2\) compressed to 2,200 psig
  - 8 stages (2.23 to 1.48 stage pressure ratios)
  - Intercooling in each stage
    - Water knockout in first 3 stages
  - TEG dehydration unit between stages 4 and 5
    - 300 ppmw H\(_2\)O in CO\(_2\) product
Advanced Stripper Alternative Process Configuration

Optimization & Heat Integration

Objective: Max. Net efficiency
Constraint: CO$_2$ removal ratio $\geq$ 90%
Decision Variables (17): Bed length, diameter, sorbent and steam feed rate

<table>
<thead>
<tr>
<th></th>
<th>w/o heat integration</th>
<th>Sequential</th>
<th>Simultaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net power efficiency (%)</td>
<td>31.0</td>
<td>32.7</td>
<td>35.7</td>
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<tr>
<td>Net power output (MW$_e$)</td>
<td>479.7</td>
<td>505.4</td>
<td>552.4</td>
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<tr>
<td>Electricity consumption$^b$ (MW$_e$)</td>
<td>67.0</td>
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<td>80.4</td>
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Base case w/o CCS: 650 MW$_e$, 42.1 %
Simultaneous Optimization of Materials & Process

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<th># Member Stages</th>
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<td>2500</td>
<td>28</td>
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The diagram shows a power plant with a flue gas being processed through membranes (M1, M2, M3) for CO$_2$ separation, with CO$_2$ to storage and to stack.
## Simultaneous Optimization of Materials & Process

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<td>2600</td>
<td>74</td>
<td>9.5%</td>
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![Diagram of Power Plant](image)

- **Power Plant**
- **Flue Gas**
- **CO$_2$ to Storage**
- **Compressors**
- **To Stack**
## Simultaneous Optimization of Materials & Process

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</tr>
<tr>
<td>New</td>
<td>2600</td>
<td>74</td>
<td>14%</td>
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### Membrane Diagram

- **Power Plant**
- **Flue Gas**
- **Compressors**
- **CO$_2$ to Storage**
- **To Stack**
Maximizing the learning at each stage of technology development

- **Early stage R&D**
  - Screening concepts
  - Identify conditions to focus development
  - Prioritize data collection & test conditions

- **Pilot scale**
  - Ensure the right data is collected
  - Support scale-up design

- **Demo scale**
  - Design the right process
  - Support deployment with reduced risk
Carbon Capture Pilot Plant Testing
Sequential Design of Experiments to Maximize Learning

Model + Experiments + Statistics
Ensure right data is collected
Maximize value of data collected

Early Stage Systems Design & Optimization
DOCCS Transformational Carbon Capture Projects

Prior CI Width: 10.5 ± 1.5
Posterior CI Width: 4.4 ± 0.4
CO₂ Utilization Provides Revenue Stream

- Cost of Electricity Generation
- Increased Cost due to Capture & Storage
- Offset to Cost of Electricity
- Net Cost of Electricity Generation

- Power Plant
- Flue Gas
- CO₂ Capture Process
- CO₂ Sequestration
- Company Utilizing CO₂
- Benefits
  - Value Added to Company’s Products
  - Beneficial Goods and Services

Steps:
- Combustion
- Capture
- Purification
- Compression
- Transportation
- Utilization
An Evolving Energy Ecosystem

Coordinated Energy Systems

- Nuclear: 807 Billion kWh
- Coal: 1,146 Billion kWh
- Natural Gas: 1,468 Billion kWh
- Wind: 275 Billion kWh
- Hydropower: 292 Billion kWh
- Other: 123 Billion kWh

Total: 4,178 Billion kilowatt-hours (kWh)

Data source: EIA, 2018

Tightly Coupled Hybrid Energy Systems

- Nuclear Reactors (LWR, SMRs)
- Gas Turbine Combined Cycle
- Coal, Oil, or Bio-Fired
- Concentrated Solar
- Wind
- PV Solar
- Energy Storage
- Chemical Process
- Storage
- Hybrid System Demand Control
- Electrical Grid
- Power Generation
- Thermal Reservoir
- Energy Storage
- Electricity Consumers

Data source: EIA, 2018
Process Intensification & Modularization

- **Intensification** smaller, cleaner, and more energy-efficient technology
  - Reactive distillation
  - Dividing wall columns
  - Rotating packed bed
  - Microreactors

- **Modular design**
  - “Numbering up” instead of scaling up
  - Reduced investment risk
  - Improved time to market
  - Increased flexibility
  - Improved safety
  - Reduced on-site construction

Figure from Rawlings et al., 2019
Process Intensification: Reactive Distillation

https://www.rvo.nl/sites/default/files/2013/10/Process%20Intensification%20Transforming%20Chemical%20Engineering.pdf
Advanced System Design & Optimization

Hierarchical Process Model Library

Steady State

Dynamic Model

Model Customization

Conceptual Design via Superstructure

Process Design & Optimization

Process Integration

Dynamics & Control

Algebraic Modeling Language
Basic blocks combine to model complex, intensified units
Kaibel Column Conceptual Design Example

- **Components:** Methanol, ethanol, n-propanol, n-butanol
  - 99% purity for each component
- 42 million combinations
- GDP model written using Pyomo.GDP
  - 5715 constraints
    - 2124 nonlinear
  - 100 disjunctions
  - 3599 variables
    - 178 binary
    - 3421 continuous
- Solved in **639 sec using GDPopt-LOA solver**
  - Logic-based outer approximation algorithm
  - 4 iterations
- Resulting design:
  - 46 trays (21% reduction vs. base case)
  - Dividing wall between 12th and 26th tray
  - Feed at 18th tray
  - Side outlets at 13th and 22nd trays

Optimal Design Kaibel Column reduces energy consumption by more than 40% compared to 2 columns
Challenges & Opportunities

Market Risk

Scalability

Variability of CO₂ streams

Technology Stability with Contaminants

Process Intensification System Development

Life Cycle Analysis
Conclusion

- Economics & Viability are $f$ (system)
- Optimal system = $f$ (materials, technology, concentration, operational approach)

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