Delivering over 90% CO$_2$ capture – learnings from modelling and pilot plant studies

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Technology development & delivery

**Process modelling**
Develop understanding of the impacts on cost and technical performance

**Demonstration**
Demonstrates feasibility and develop understanding of plant operation

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**Process modelling in gPROMS and MATLAB**

![Diagram](image)

**Operating Cost Fraction (%)**
- Indirect capture via negative emissions

- Operating data from demo plant

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Beyond 90% capture: Possible, but at what cost?

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En Route to Zero Emissions for Power and Industry with Amine-Based Post-combustion Capture

David Danaci II, Mai Bui II, Camille Petit,8 and Niall Mac DowellII

Start-up and shutdown protocol for power stations with CO2 capture

(under review)
History of carbon capture and storage (CCS)

Absorption-based CO₂ capture technology was patented in 1930.

Although studies consider different applications and solvents, most studies have assumed a CO₂ capture rate of 90%.

Where did this assumption come from?

* don’t mention capture rates
Origins of the 90% capture rate assumption

Earlier work on CCS arbitrarily chose specific capture rates.

The 90% CO₂ capture rate has now become ubiquitous in the literature, which has led to doubt around the feasibility of >90% capture.

Emission sources vary in size & \( \text{CO}_2 \) concentration

<table>
<thead>
<tr>
<th>Application</th>
<th>Flow rate [kg/s]</th>
<th>( y_{\text{CO}_2} ) [%mol]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 MW NGCC</td>
<td>791</td>
<td>4.0</td>
</tr>
<tr>
<td>500 MW NGCC 50% Exhaust Gas Recycle (EGR)</td>
<td>401</td>
<td>8.2</td>
</tr>
<tr>
<td>500 MW high-rank coal</td>
<td>503</td>
<td>11.7</td>
</tr>
<tr>
<td>500 MW low-rank coal</td>
<td>1077</td>
<td>12.5</td>
</tr>
<tr>
<td>500 MW biomass</td>
<td>503</td>
<td>14.4</td>
</tr>
<tr>
<td>1 MMtpa cement</td>
<td>162</td>
<td>18.6</td>
</tr>
<tr>
<td>1 MMtpa steel</td>
<td>164</td>
<td>23.2</td>
</tr>
</tbody>
</table>

Capture cost: Effect of plant scale

Economies of scale effect apparent once gas flow >10 kg/s.

Lower capture costs ($/tCO2) at higher gas CO2 concentration.

Minor difference in capture cost trends for 90% vs 99% capture. However, capture costs for 99% capture is slightly higher.
CCGT: Effect of capture rate on cost


At 98% capture rate or higher, the main contributor to the cost of capture is the absorber column (CAPEX).

Does the effect of 99% capture rate vary with different applications?
Effect of CO\textsubscript{2} concentration on costs

Assuming constant flue gas flow rate 500 kg/s

**Capital costs:** mainly absorber cost, doubles at 99% capture. Absolute reboiler duty and amine circulation rate increases with higher gas CO\textsubscript{2} content, thus requiring more HX area.

**Operating costs:** Mainly steam costs which increase with gas CO\textsubscript{2} concentration and capture rate.

Balancing costs: >90% capture vs CO$_2$ removal

In a net-zero emissions future, residual CO$_2$ emissions would need to be offset via CO$_2$ removal from the atmosphere.

Depending on the CO$_2$ concentration of the point source, using higher CO$_2$ capture rates will likely be more cost effective than paying for CDR offsets. At this stage, CDR costs highly uncertain.

The impact of an investment credit (e.g., §48A) lessens when there is access to cheap capital (e.g., low CRF).

An investment credit is of greater benefit to projects dealing with flue gases that have lower CO$_2$ concentration (e.g., gas-power) compared to concentrated sources of the same size.

For CO$_2$ capture from concentrated point sources (e.g., $y_{CO_2} = 30$ mol%), combining §48A with the §45Q tax credit* is close to being economically feasible under realistic CRF scenarios, i.e., 12%.

* This study assumed $50/\text{tCO}_2$, but current proposals in Congress could boost 45Q as high as $175/\text{t}$

CRF 12% corresponds to 11% interest rate and annuity period of 25 years

In order for the TAC to break-even with a $50/tCO\textsubscript{2} 45Q tax credit at 99% capture rate:

- Gas-fired power CCS needs 70% reduction in both OPEX and CAPEX
- Coal-fired power CCS needs a 25% reduction in OPEX and 68% reduction in CAPEX

This study was based on a conventional process using 30 wt% MEA.

In addition to financial incentives, cost reductions could be achieved with advanced solvents in modern process topology & design.
Effect of flexible operation on CO$_2$ capture performance

Process modelling: 
*Steady state* models only

Demonstration tests:
*Studied CO$_2$ capture performance under steady state and dynamic conditions*

- Process modelling in gPROMS and MATLAB
- Operating data from demo plant
- Indirect capture via negative emissions

Flexible operation of CO$_2$ capture plants

We have studied the effects of flexible operation on CO$_2$ capture performance.

- Higher ramp rates
- Shorter start-up & shut down times
- Minimise CO$_2$ emissions
- Ability to maximise power production
- Lower minimum load
- Part-load efficiency
- Shorter minimum uptime and runtime

Electricity grids with high levels of intermittent renewables will require dispatchable low carbon electricity.

Power plants with CCS provides greater flexibility.

Improves economic performance of system.

We have studied the effects of flexible operation on CO$_2$ capture performance.
Flexible operation of a demonstration-scale CO$_2$ capture plant

**CHP mode**
- 4 mol% CO$_2$ gas
- Captures 80 t$_{CO_2}$/day

**RCC mode**
- 12 mol% CO$_2$ gas
- Captures 275 t$_{CO_2}$/day

TCM CO₂ capture facility, Mongstad Norway

Absorber | RCC stripper
---|---
Cross section dimensions | 3.55 m x 2 m | 1.3 m (2017) 2.2 m (2020)
Packing height (m) | 24 m (2017) 18 m (2020) | 8
Packing type | Flexipac 2X (structured) | Flexipac 2X (structured)

Capture capacity of 80 tonnes CO₂ per day

<table>
<thead>
<tr>
<th>Flue gas component</th>
<th>CHP component</th>
<th>mole %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td></td>
<td>78.6</td>
</tr>
<tr>
<td>CO₂</td>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>H₂O</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>O₂</td>
<td></td>
<td>14.4</td>
</tr>
<tr>
<td>Ar</td>
<td></td>
<td>0.9</td>
</tr>
</tbody>
</table>

2017 tests used 30 wt% MEA
2020 tests used Cesar-1, containing 27 wt% AMP+ 13 wt% PZ in June, and 26 wt% AMP+ 9.5 wt% PZ in November
Flexible operation of the CO$_2$ capture plant

There are also strategies useful for operating the capture plant in a “load following” manner.

Previous MEA test campaign at TCM was conducted in July 2017.

This studied the performance of the TCM plant during three flexible operation tests:
- Step-change of steam flow
- Time-varying solvent regeneration
- Variable ramp rate

Off-peak electricity prices:
Solvent is regenerated, reducing power output → expect lower flue gas flow rates.

Peak electricity prices:
accumulate CO$_2$ in the amine. Power output increases, burning more fuel → higher flue gas flow.

Note: Operating more flexibly means the steady state capture rate cannot provide an indication of residual CO$_2$ emissions. Need to calculate cumulative amounts.
Time varying solvent regeneration

Capture rates
- 97% ICL_7
- 14.5% ICL_8
- 89% ICL_9

Off-peak mode:
- STR T: up
- lean loading: down
- CO₂ capture rate: up
- ABS T: up

Peak mode:
- STR T: down
- lean loading: up
- CO₂ capture rate: down
- ABS T: down

**Off-peak:** solvent regenerated and lean CO$_2$ loading reduced.

**Reboiler temperature:** 124.1 °C  
**CO$_2$ capture rate:** 89–97%  
**Lean CO$_2$ loading:** 0.16 mol$_{CO_2}$/mol$_{MEA}$

**Peak:** CO$_2$ is “stored” in solvent and lean CO$_2$ loading increases.

**Reboiler temperature:** 109.5 °C  
**CO$_2$ capture rate:** 14.5%  
**Lean CO$_2$ loading:** 0.48 mol$_{CO_2}$/mol$_{MEA}$

**Rich CO$_2$ Loading:** 0.52–0.53 mol$_{CO_2}$/mol$_{MEA}$

**Reboiler duty:** 3.93–4.11 MJ/kg CO$_2$

**Cumulative CO$_2$ capture rate:** 66.5%

For max cumulative CO$_2$ capture, we need to optimise the duration between modes

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Performance during start-up and shut down

Rise in the frequency of start-up and shut down cycles will be expected with higher levels of intermittent renewables.

If this significantly increases CO$_2$ emissions, it would undermine the value proposition of CCS.

In 2020, we studied the effect of start-up & shut down on CO$_2$ emissions at TCM.

Studying the following: (i) hot vs cold start-up, (ii) timing of steam availability (conventional vs preheat vs delayed), (iii) solvent inventory capacity, (iv) start-up solvent loading/composition.

Bui, M. & Mac Dowell, N., under review, Start-up and shutdown protocol for power stations with CO$_2$ capture, IEAGHG report.
Effect of process dynamics of the capture performance

As shown previously, balancing the duration of capture modes is important in ensure capture requirements are met. In the above test, the plant cumulatively captured 90% of the feed CO$_2$, despite online capture rate varying from 99% to 83%, then increasing to 90% and 96%.

Bui, M. & Mac Dowell, N., under review, Start-up and shutdown protocol for power stations with CO$_2$ capture, IEAGHG report.
Improving capture performance during start-up

Cold start-up with 42 m³ solvent inventory

Cold start-up with preheating and using 45 m³ inventory

Steam flow started at the same time as the flue gas flow, i.e., “conventional” start-up.

Steam flow started earlier than the flue gas flow rate to simulate “preheating”.

Bui, M. & Mac Dowell, N., under review, Start-up and shutdown protocol for power stations with CO₂ capture, IEAGHG report.
Improving capture performance during start-up

Cold start-up with 42 m³ solvent inventory

Conventional start-up: Reboiler is not at the set-point temperature at the time FG starts, causing the CO₂ capture rate to drop from 99.8% to 44.6%, before increasing again to 87%.

Cold start-up with preheating and using 45 m³ inventory

Start-up with preheating: Reboiler reaches set-point temperature much quicker. The CO₂ capture rate remains stable, starting at 99.3% before reduces slightly to 92.5%.

Bui, M. & Mac Dowell, N., under review, Start-up and shutdown protocol for power stations with CO₂ capture, IEAGHG report.
Conclusions: Delivering over 90% CO$_2$ capture

Process modelling and plant demonstrations show that high CO$_2$ capture rates of 95 to 99% are technically and economically feasible.

The modelling work shows CO$_2$ capture costs for different applications and illustrates the effect of plant scale (i.e., flue gas flow rate), flue gas CO$_2$ concentration and capture rate.

Economies of scale has a clear impact at >10 kg/s gas flow rates, also opportunities for lower capture costs for industrial capture applications with higher gas CO$_2$ concentration.

When capture rate increases from 90% to 99%, the main contribution to the increase in capture costs is the larger absorber column, with a minor increase in steam costs.

A balanced portfolio of investment credits and tax credits will likely be required. There is also the potential for further cost reductions through using advanced solvents, modern plant topology and process intensification.

The demonstration studies at TCM shows the importance of considering cumulative capture rate, particularly during flexible operation. We also demonstrated different operating strategies that can be used to achieve higher CO$_2$ capture rates during flexible operation, e.g., preheating before start-up, lower loading upon start-up, optimising duration of time periods.
Future considerations: Delivering over 90% CO₂ capture

In countries with net-zero targets, higher CO₂ capture rates of 95% or higher will be essential to reduce the burden on CO₂ removal from the atmosphere (may be more expensive and limited in scale).

We have mainly focused on increasing CO₂ capture rates of MEA-based absorption for post-combustion capture applications, i.e., power plants and industry.

We also need a systems approach to reducing CO₂ emissions. The supply chain CO₂ emissions associated with the fuel (e.g., natural gas, coal, biomass) will also have an impact on the actual CO₂ reduction potential and will be an important consideration for further work, e.g., integrate LCA with process modelling.

Future work could explore the potential for maximising CO₂ capture rate in other non-combustion applications for CO₂ capture processes, e.g., hydrogen production.

The studies on flexible operation demonstrate that there is a temporal element that needs to be accounted for when determining CO₂ emissions and cumulative CO₂ capture %. This will likely have an impact on regulation and policy for CO₂ emissions from power and industry.