Delivering over 90% CO_2 capture – learnings from modelling and pilot plant studies

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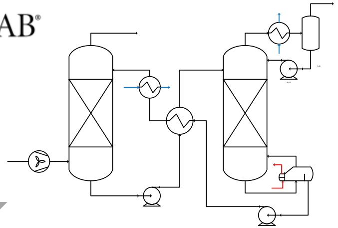
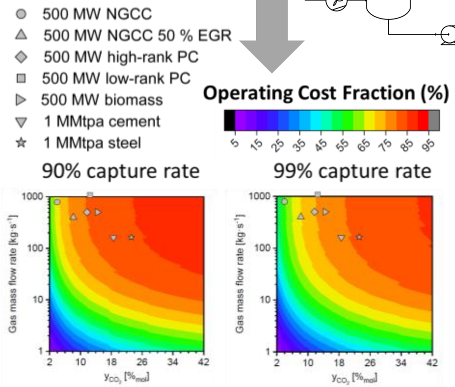
Technology development & delivery

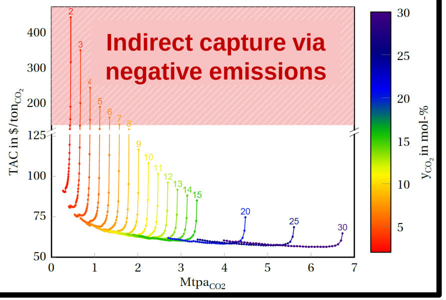
Process modelling
Develop understanding of the impacts on cost and technical performance

Demonstration
Demonstrates feasibility and develop understanding of plant operation

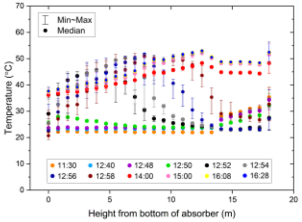
Process modelling in gPROMS and MATLAB

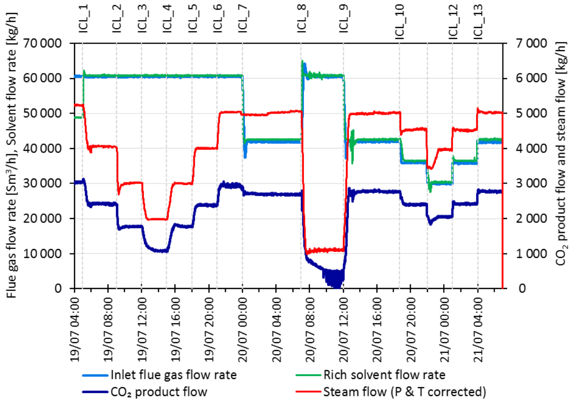






Operating data from demo plant





Brandl, P., Bui, M., Hallett, J. P. & Mac Dowell, N. (2021). *IJGGC,* 105, 103239.
Danaci, D., Bui, M., Petit, C. & Mac Dowell, N. (2021). DOI: 10.1021/acs.est.0c07261

Bui, M., Flø, N. E., de Cazenove, T., Mac Dowell, N., (2020). International Journal of Greenhouse Gas Control, 93, 102879.

Modelling – steady state

International Journal of Greenhouse Gas Control 105 (2021) 103239

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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

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Cite This: https://doi.org/10.1021/acs.est.0c07261 Read Online

Demonstration tests – steady state & dynamic

International Journal of Greenhouse Gas Control 93 (2020) 102879

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Demonstrating flexible operation of the Technology Centre Mongstad (TCM) CO_2 capture plant

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Start-up and shutdown protocol for power stations with CO_2 capture

(under review)

History of carbon capture and storage (CCS)

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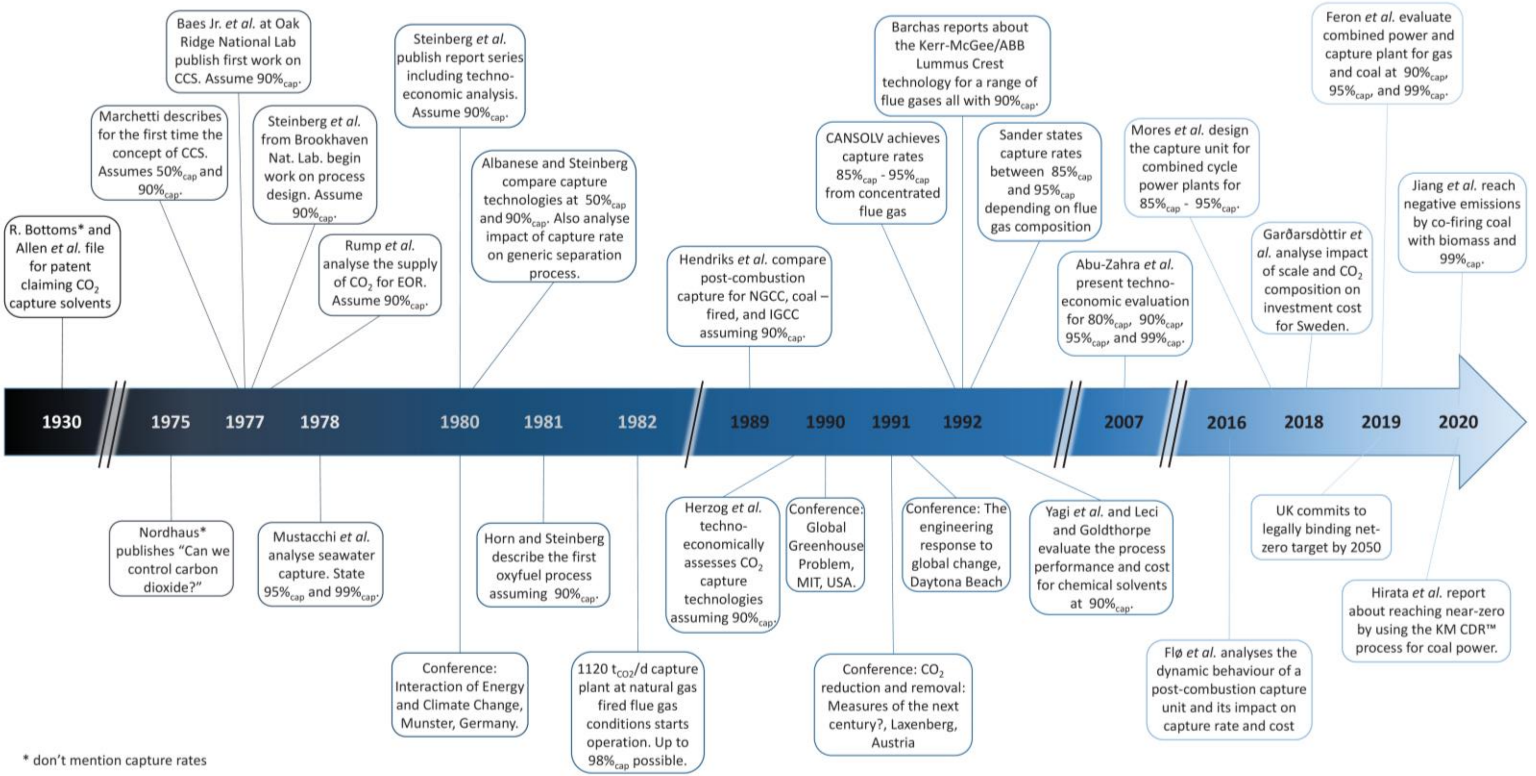
Absorption-based CO_2 capture technology was patented in 1930.

Although studies consider different applications and solvents, most studies have assumed a CO_2 capture rate of 90%.

Where did this assumption come from?



Brandl, P., Bui, M., Hallett, J. P. & Mac Dowell, N. (2021). Beyond 90% capture: Possible, but at what cost? *International Journal of Greenhouse Gas Control,* 105**,** 103239.

Origins of the 90% capture rate assumption

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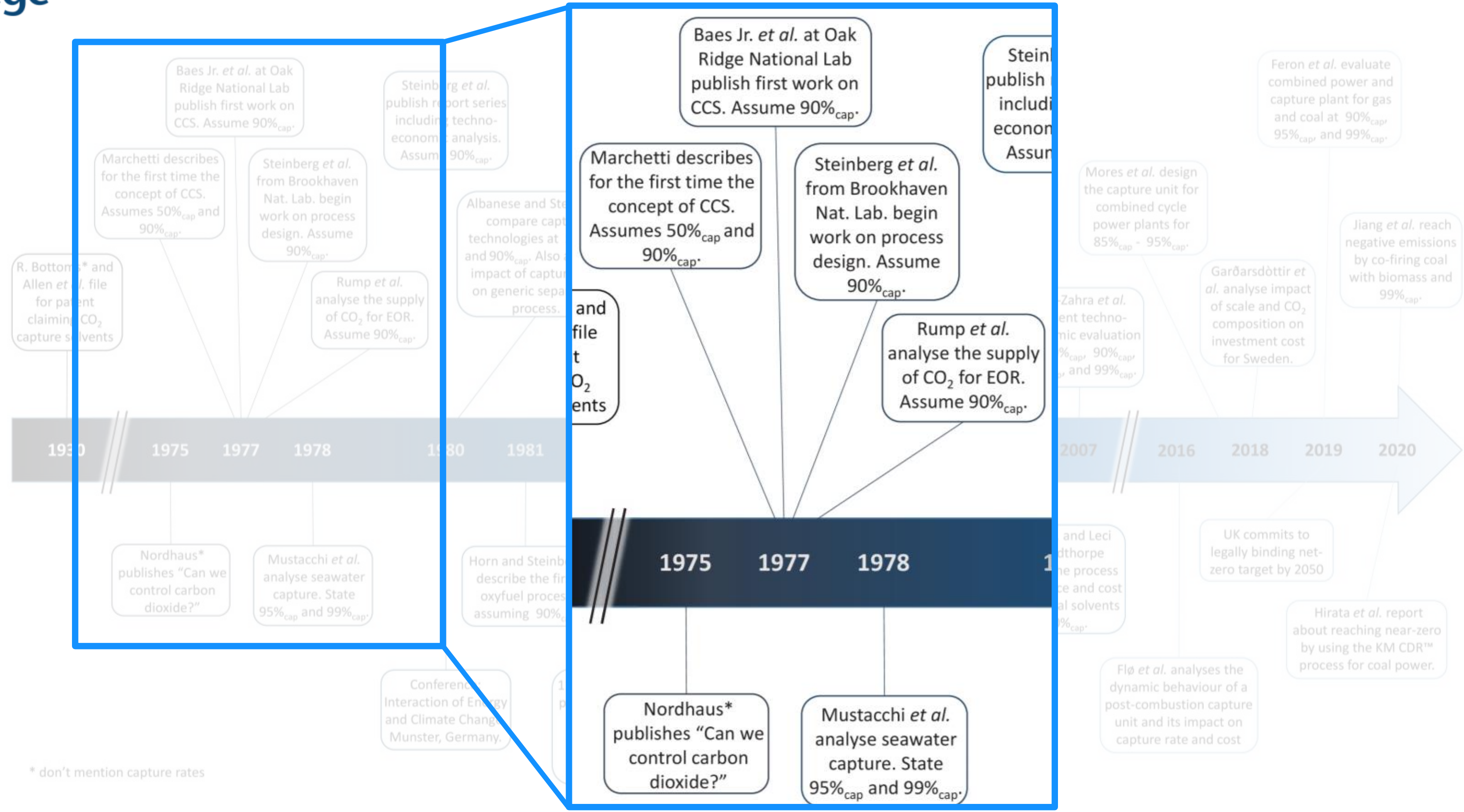
Earlier work on CCS arbitrarily chose specific capture rates.

The 90% CO_2 capture rate has now become ubiquitous in the literature, which has led to doubt around the feasibility of >90% capture.



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Emission sources vary in size & CO_2 concentration

Application	Flow rate [kg/s]	y_{CO2} [$\%_{mol}$]
500 MW NGCC	791	4.0
500 MW NGCC 50% Exhaust Gas Recycle (EGR)	401	8.2
500 MW high-rank coal	503	11.7
500 MW low-rank coal	1077	12.5
500 MW biomass	503	14.4
1 MMtpa cement	162	18.6
1 MMtpa steel	164	23.2

Danaci, D., Bui, M., Petit, C. & Mac Dowell, N. (2021). *Environmental Science & Technology*.
DOI: 10.1021/acs.est.0c07261

Capture cost: Effect of plant scale

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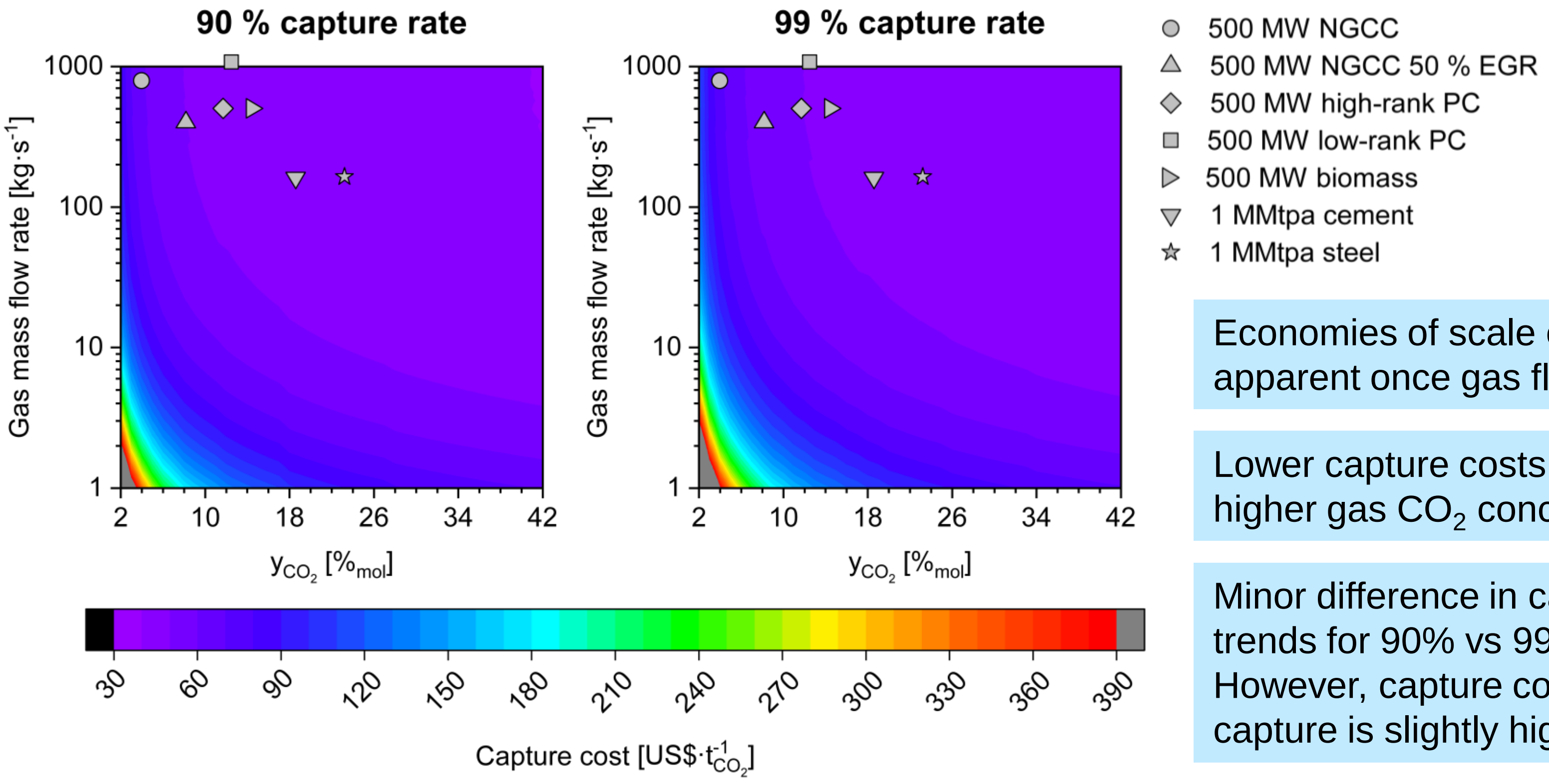

Economies of scale effect apparent once gas flow >10 kg/s.

Lower capture costs ($/tCO2) at higher gas CO_2 concentration.

Minor difference in capture cost trends for 90% vs 99% capture. However, capture costs for 99% capture is slightly higher.

Danaci, D., Bui, M., Petit, C. & Mac Dowell, N. (2021). *Environmental Science & Technology*.
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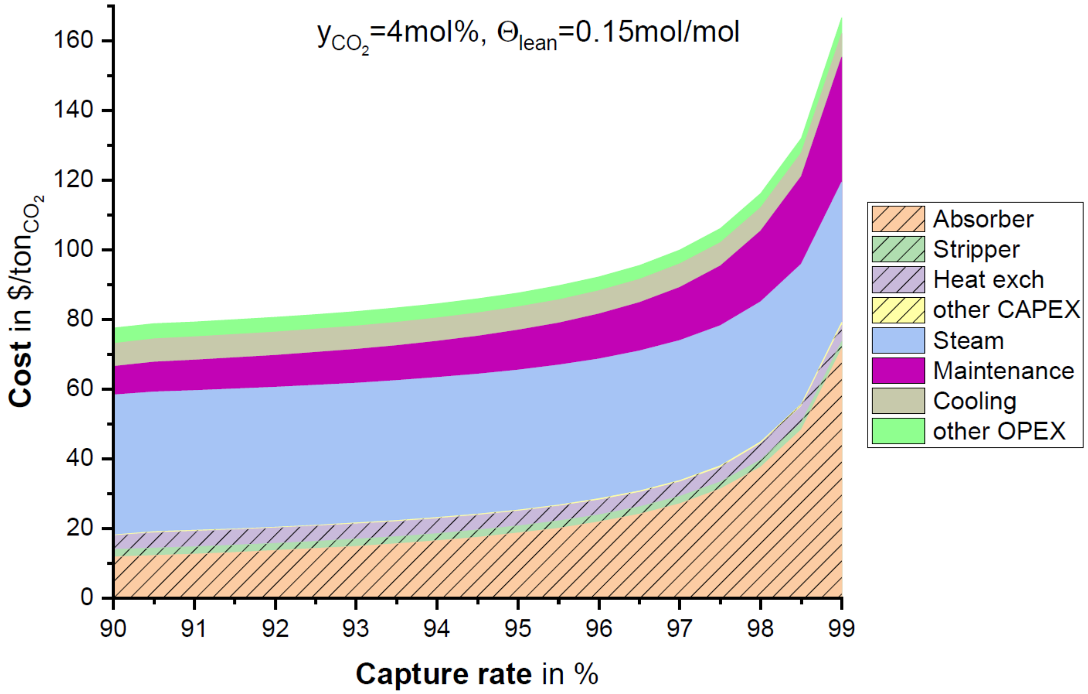
CCGT: Effect of capture rate on cost

Natural gas-fired CCGT power plant



At capture rates from 90 to 98%, the cost of steam (OPEX) is the largest contributor to the cost of capture.

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

Does the effect of 99% capture rate vary with different applications?

Brandl, P., Bui, M., Hallett, J. P. & Mac Dowell, N. (2021). Beyond 90% capture: Possible, but at what cost? *International Journal of Greenhouse Gas Control,* 105**,** 103239.

Effect of CO_2 concentration on costs

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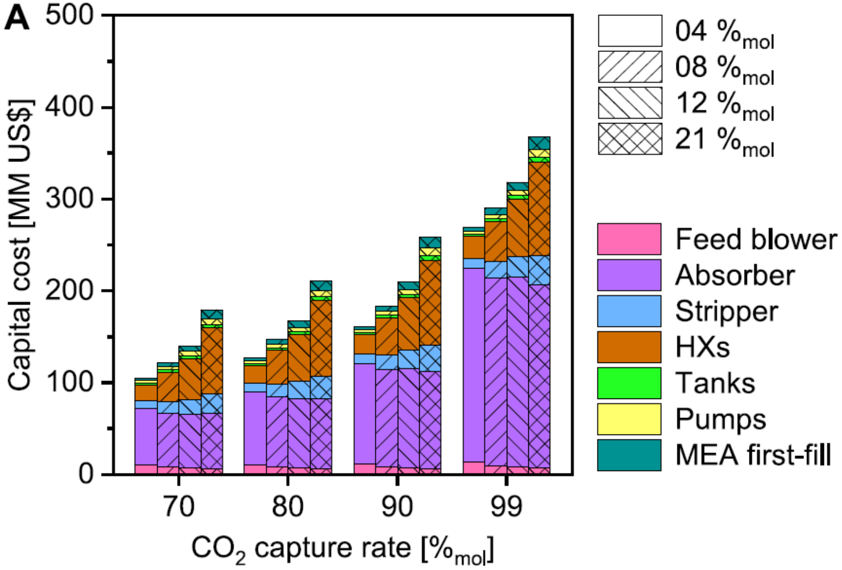
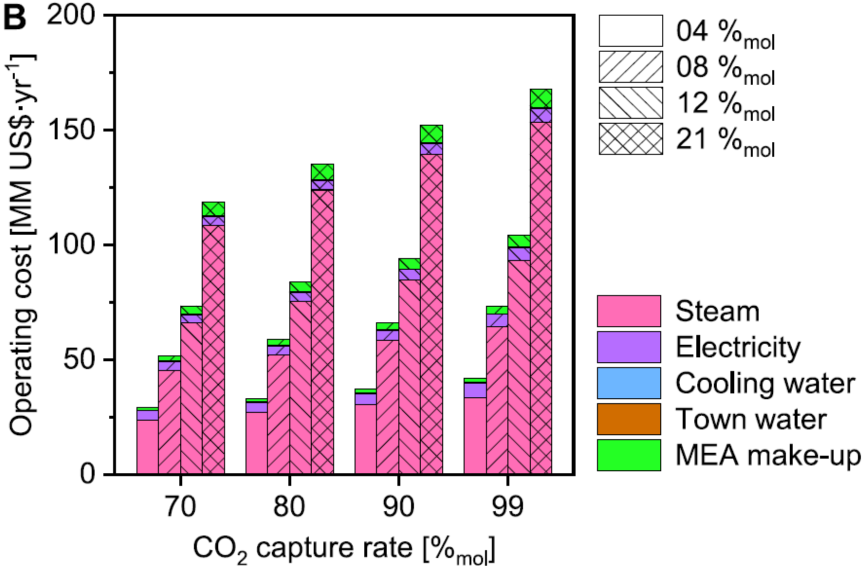
Assuming constant flue gas flow rate 500 kg/s





Capital costs: mainly absorber cost, doubles at 99% capture. Absolute reboiler duty and amine circulation rate increases with higher gas CO_2 content, thus requiring more HX area.

Operating costs: Mainly steam costs which increase with gas CO_2 concentration and capture rate.

Danaci, D., Bui, M., Petit, C. & Mac Dowell, N. (2021). *Environmental Science & Technology*. DOI: 10.1021/acs.est.0c07261

Balancing costs: >90% capture vs CO_2 removal

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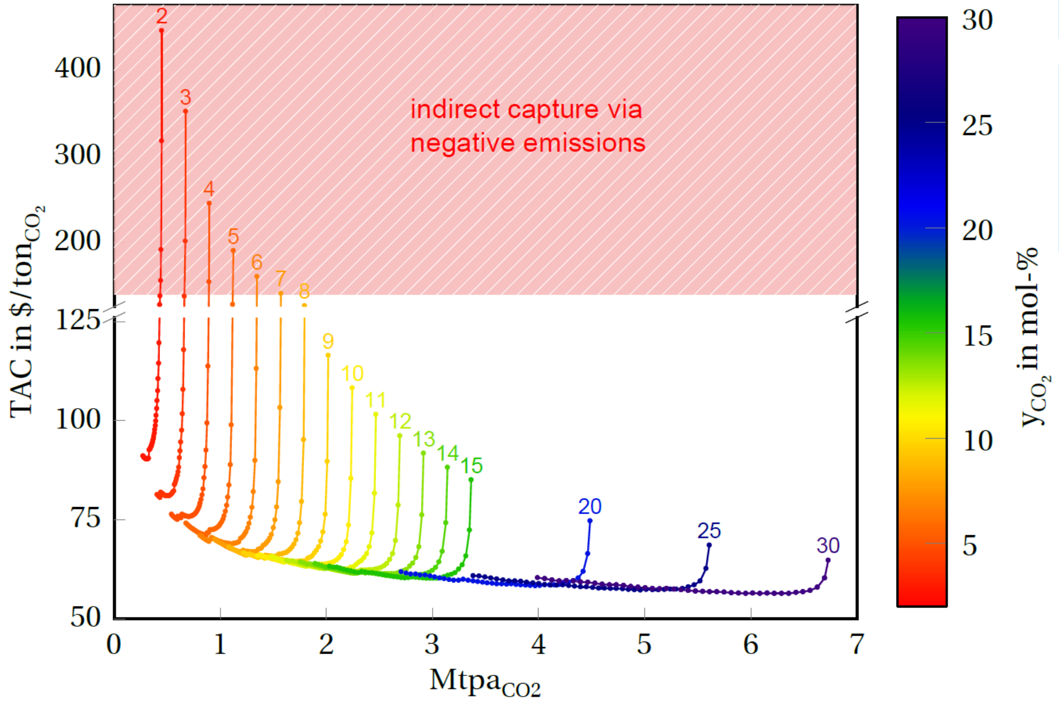
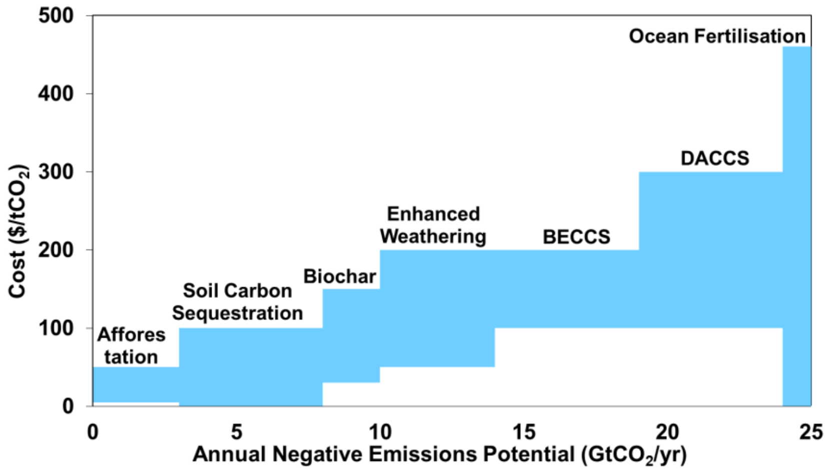


In a net-zero emissions future, residual CO_2 emissions would need to be offset via CO_2 removal from the atmosphere.

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.



Brandl, P., Bui, M., Hallett, J. P. & Mac Dowell, N. (2021). Beyond 90% capture: Possible, but at what cost? *International Journal of Greenhouse Gas Control,* 105**,** 103239.

Figure adapted from Fuss, S., et al. (2018). Environmental Research Letters, 13 (6), 063002.
Minx, J. C., et al. (2018). Environmental Research Letters, 13 (6)**,** 063001.

Impact of investment & tax credits

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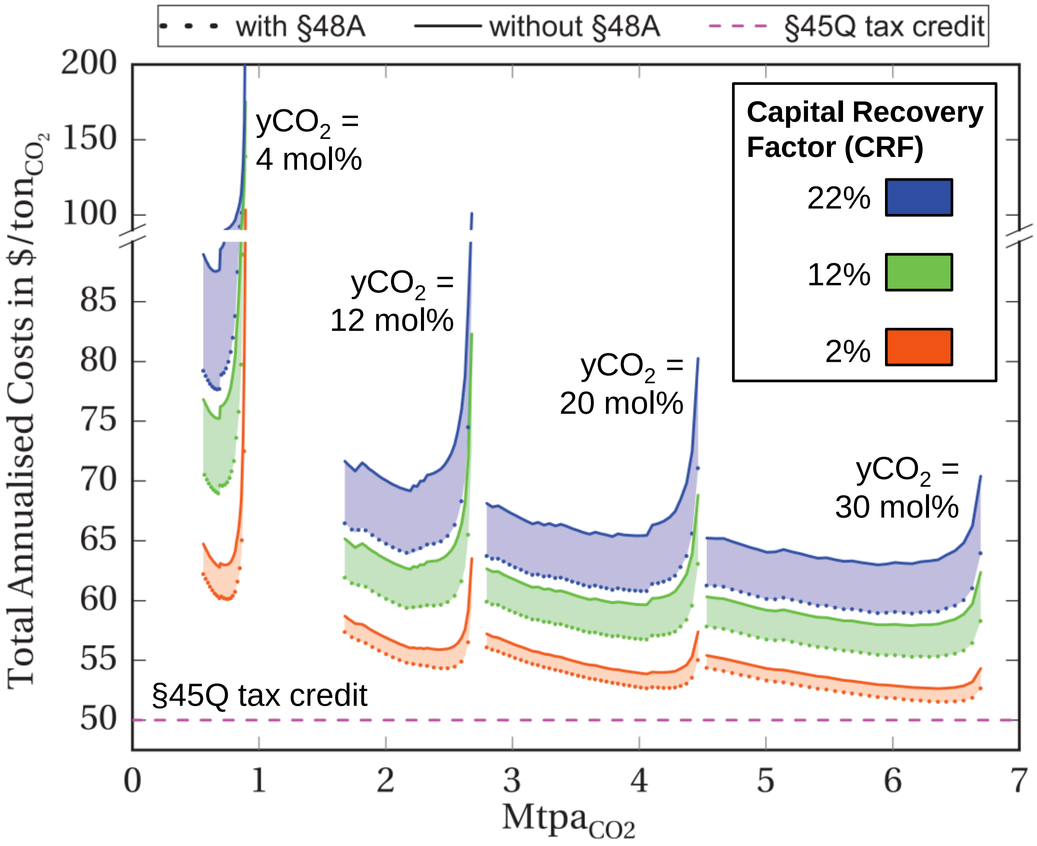
The impact of an investment credit (e.g., §48A) lessens when there is access to cheap capital (e.g., low CRF).

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_{CO2} = 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/tCO2, but current proposals in Congress could boost 45Q as high as \$175/t

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

Brandl, P., Bui, M., Hallett, J. P. & Mac Dowell, N. (2021). *International Journal of Greenhouse Gas Control,* 105, 103239.

Required reductions in CAPEX & OPEX

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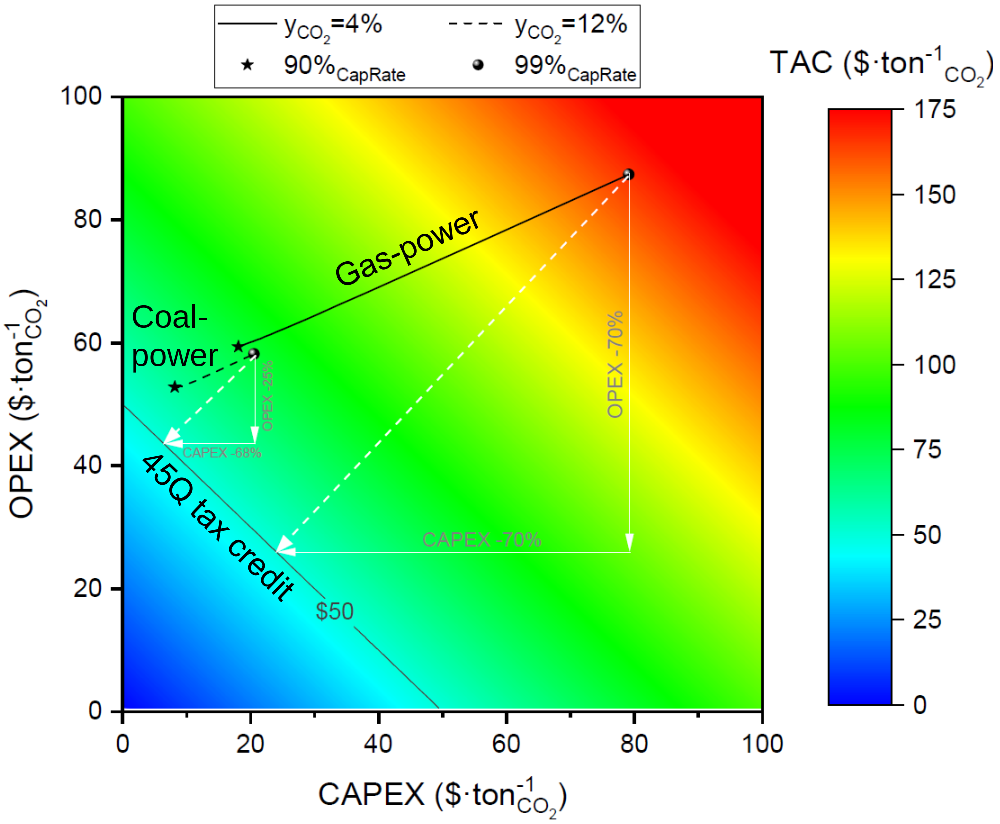
In order for the TAC to break-even with a $50/tCO_2$ 45Q tax credit at 99% capture rate:

- 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.



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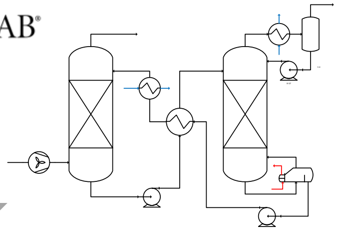
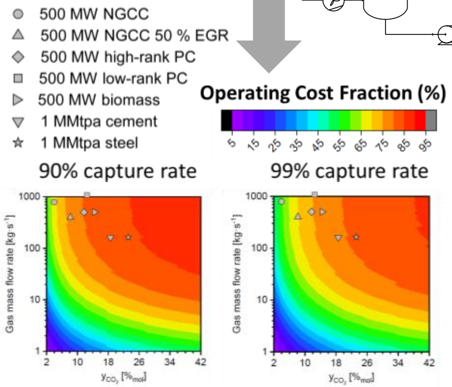
Effect of flexible operation on CO_2 capture performance

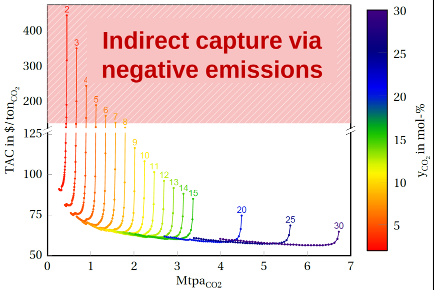
Process modelling:
Steady state models only

Demonstration tests:
Studied CO_2 capture performance under ***steady state and dynamic*** conditions

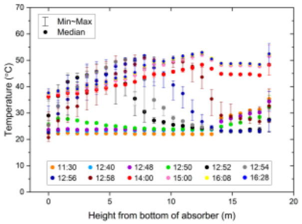
Process modelling in gPROMS and MATLAB

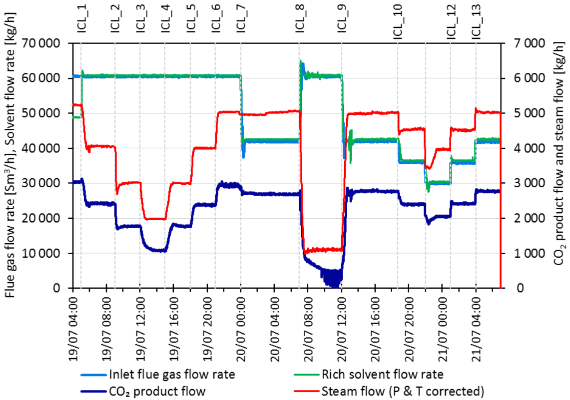






Operating data from demo plant





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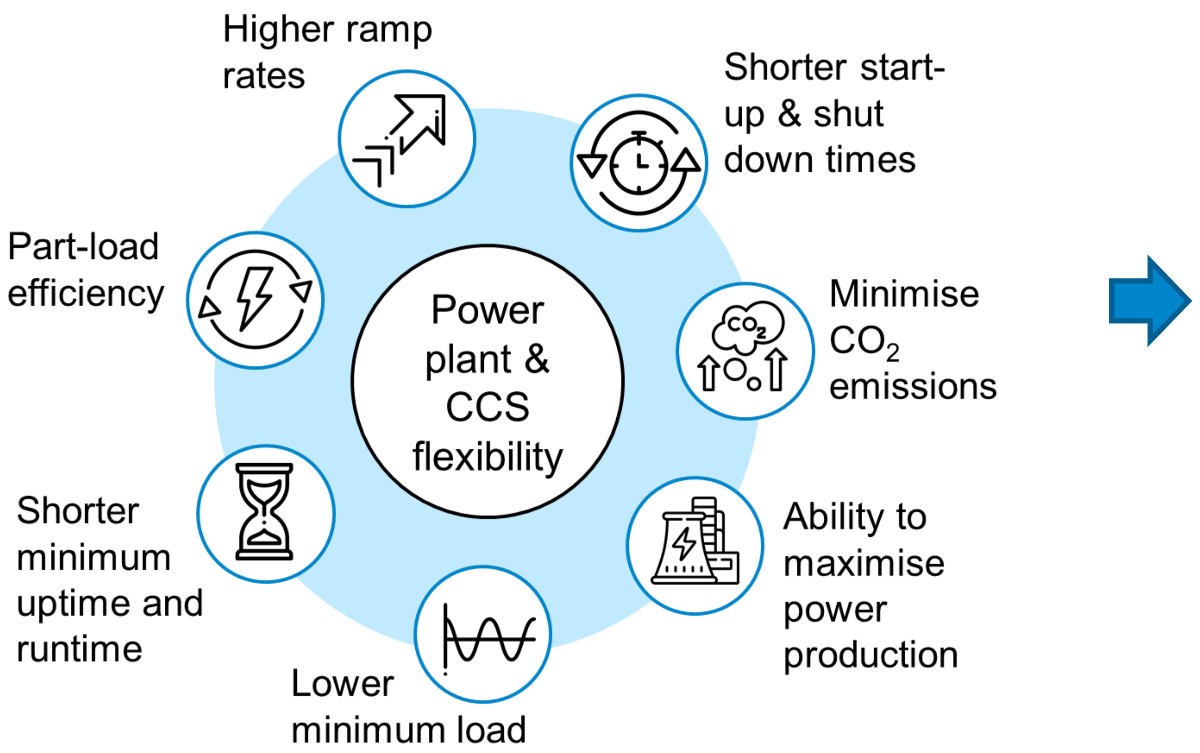
Flexible operation of CO_2 capture plants



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.

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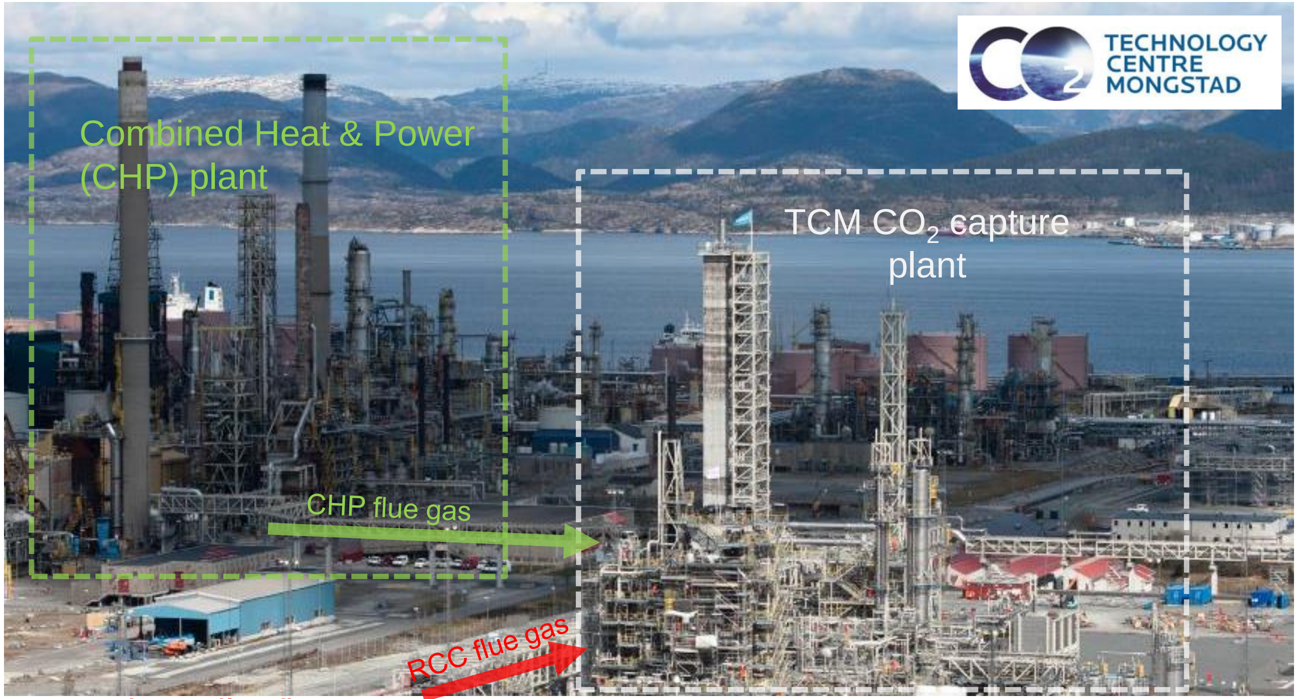
Flexible operation of a demonstration-scale CO_2 capture plant

CHP mode
4 mol% CO_2 gas
Captures 80 t_{CO2}/day

RCC mode
12 mol% CO_2 gas
Captures 275 t_{CO2}/day



Equinor oil refinery (not shown)

http://cdn3.spiegel.de/images/image-349556-860_poster_16x9-ygkk-349556.jpg

Bui, M., Flø, N. E., de Cazenove, T., Mac Dowell, N., (2020). International Journal of Greenhouse Gas Control, 93, 102879.

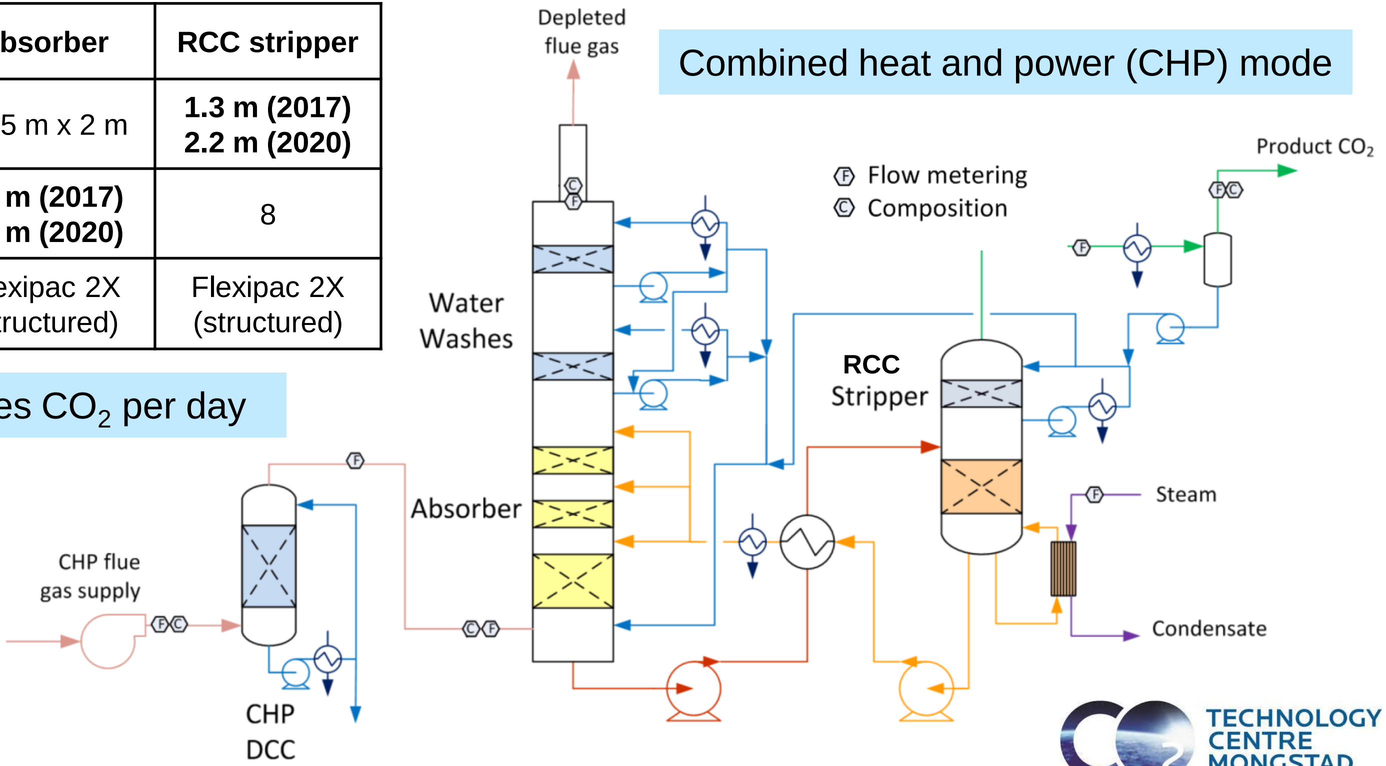
TCM CO_2 capture facility, Mongstad Norway

	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 CO_2 per day

Flue gas component	**CHP** mole %
N_2	78.6
CO_2	3.6
H_2O	2.5
O_2	14.4
Ar	0.9

Combined heat and power (CHP) mode



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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

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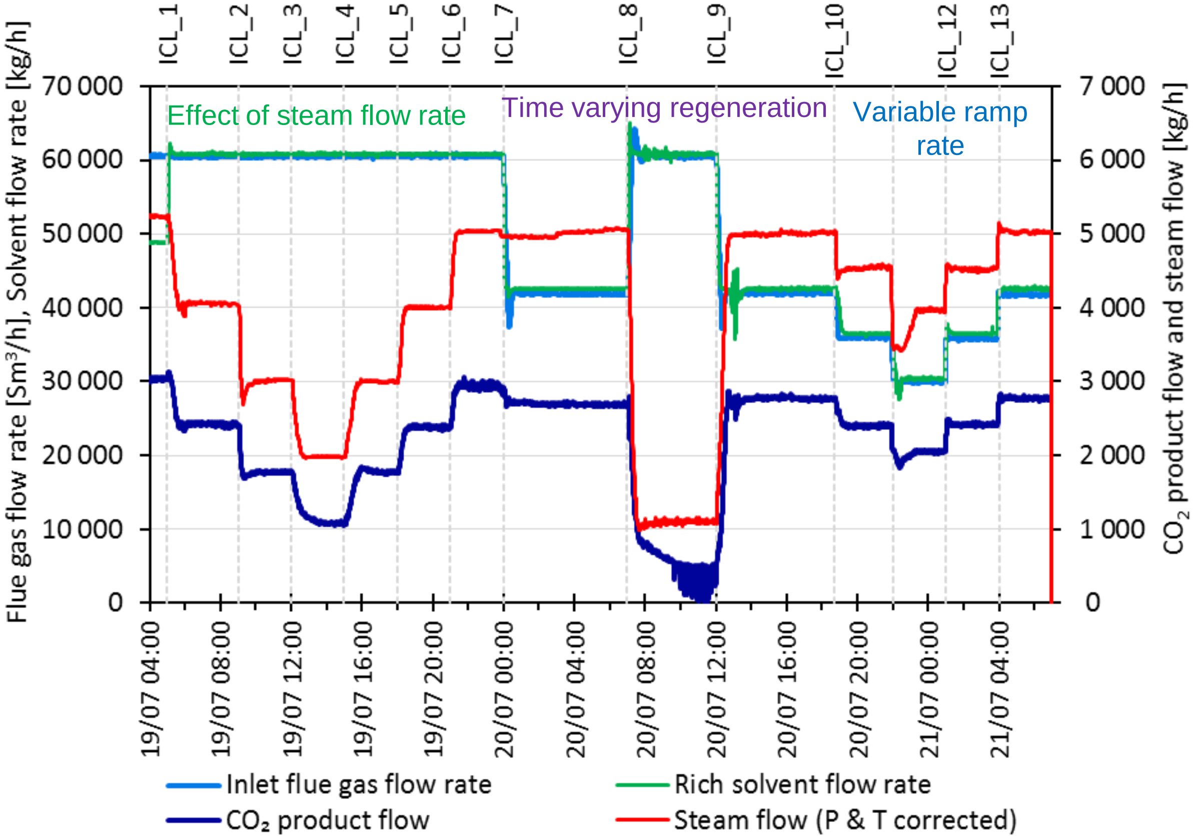
There are also strategies useful for operating the capture plant in a “load following” manner.

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



Bui, M., Flø, N. E., de Cazenove, T., Mac Dowell, N., (2020). International Journal of Greenhouse Gas Control, 93, 102879.

Time-varying solvent regeneration

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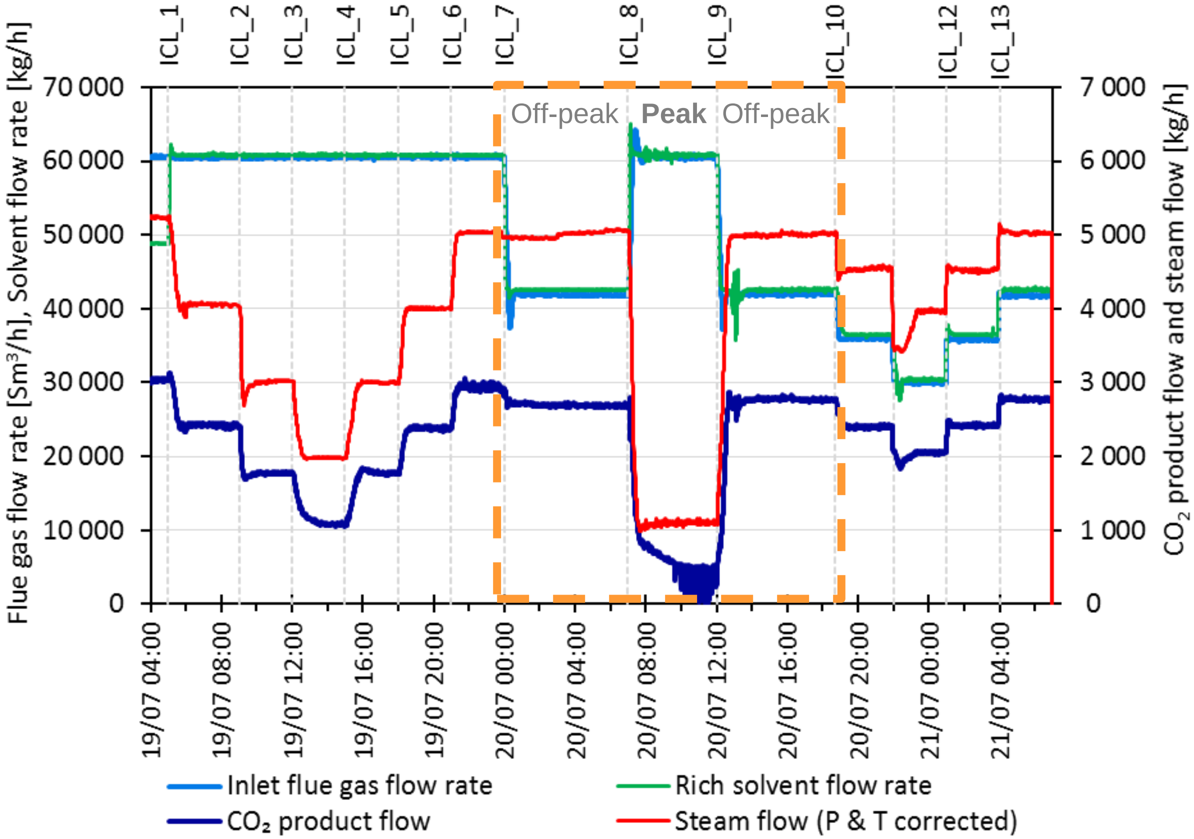
Off-peak electricity prices:
Solvent is regenerated, reducing power output → expect lower flue gas flow rates.

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.



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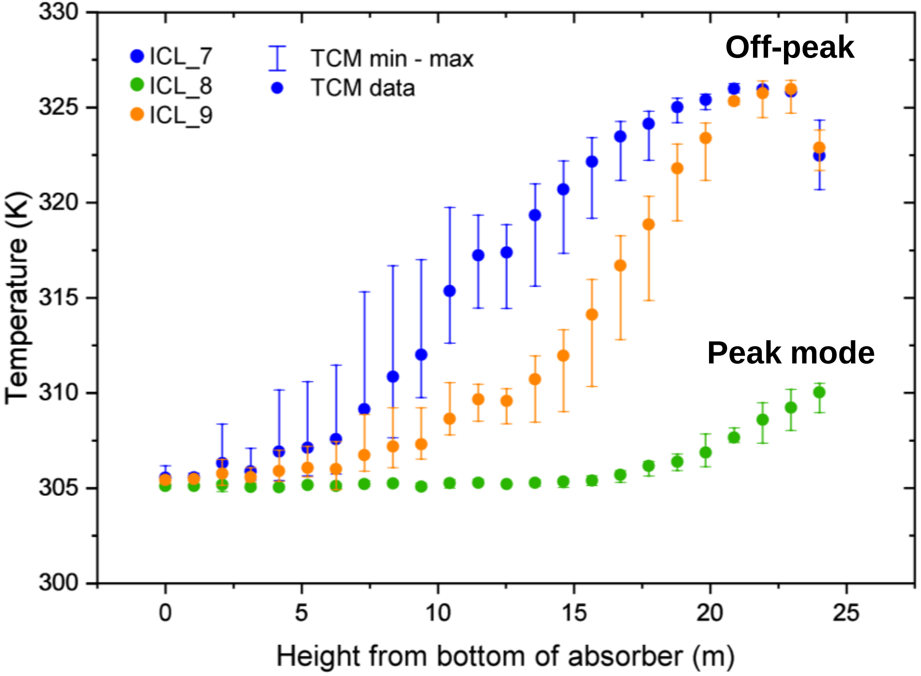
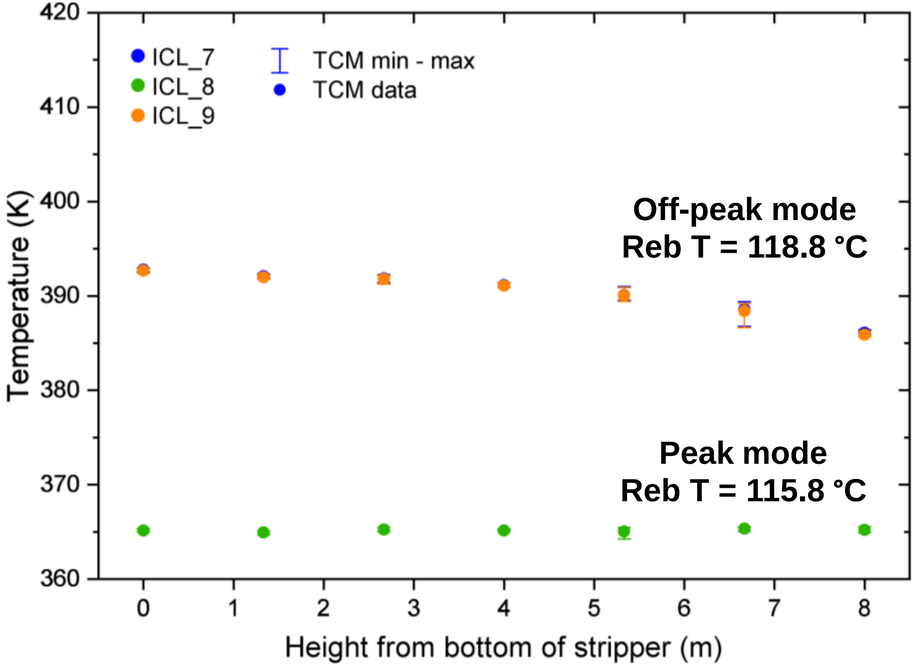
Time varying solvent regeneration

Capture rates

97% ICL_7
14.5% ICL_8
89% ICL_9

Off-peak mode:	↑ STR T	↓ lean loading	↑ CO_2 capture rate	↑ ABS T
Peak mode:	↓ STR T	↑ lean loading	↓ CO_2 capture rate	↓ ABS T





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Time-varying solvent regeneration

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_{CO2}/mol_{MEA}

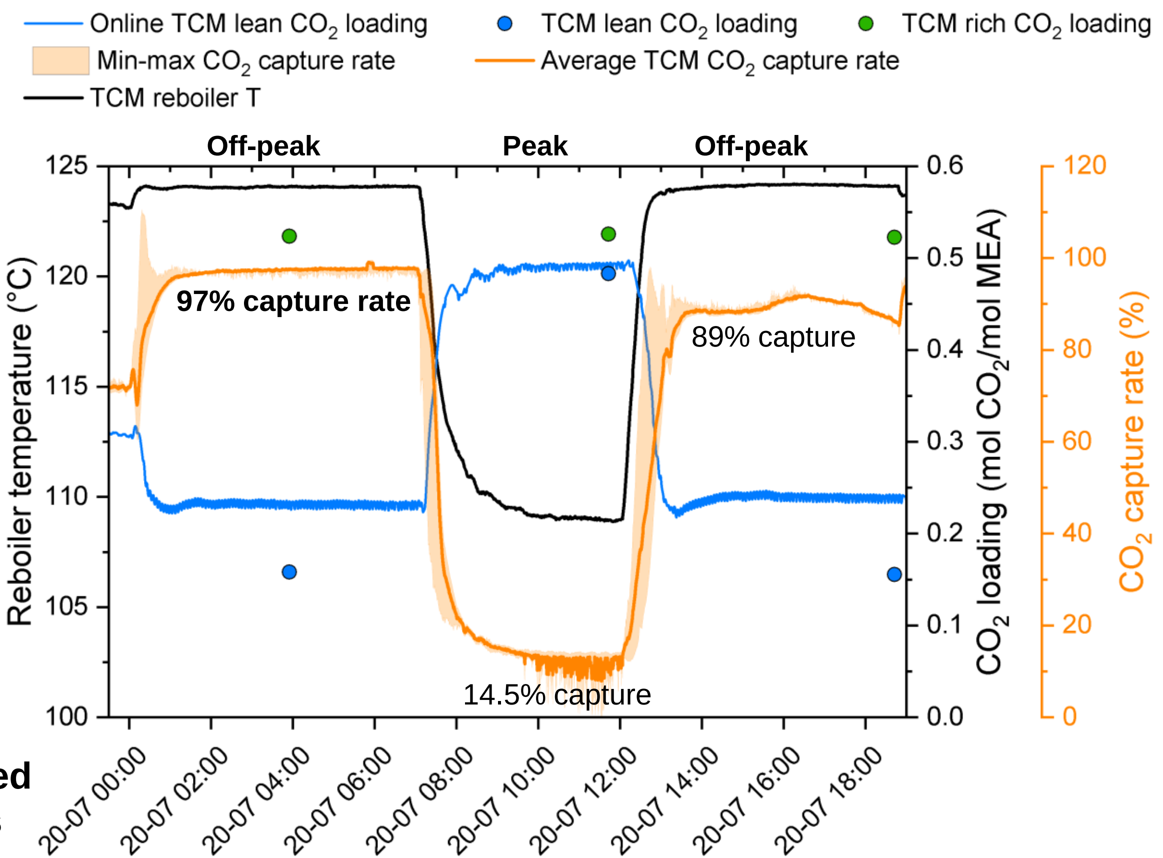
Peak: *CO_2 is "stored" in solvent and lean CO_2 loading increases.*

Reboiler temperature: 109.5 °C
CO_2 capture rate: 14.5%
Lean CO_2 loading: 0.48 mol_{CO2}/mol_{MEA}

Rich CO_2 Loading:
0.52–0.53 mol_{CO2}/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

Bui, M., Flø, N. E., de Cazenove, T., Mac Dowell, N., (2020). International Journal of Greenhouse Gas Control, 93, 102879.

Performance during start-up and shut down

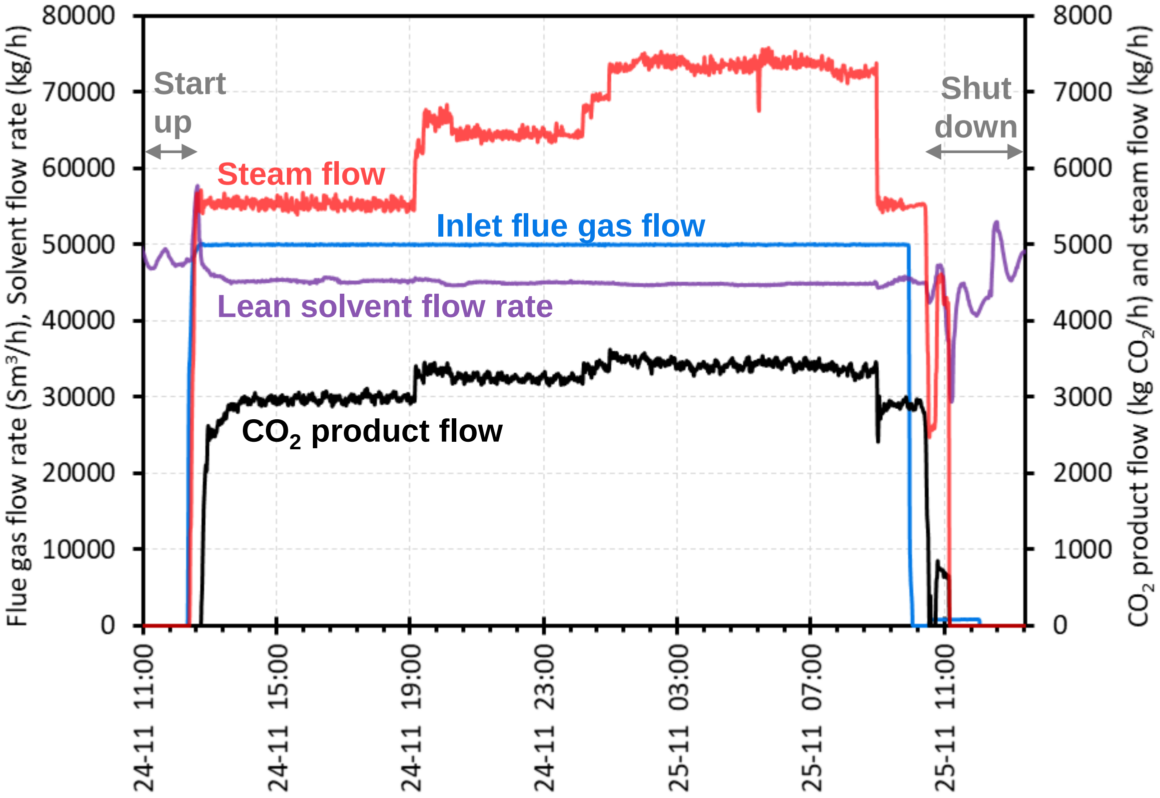
Rise in the frequency of start-up and shut down cycles will be expected with higher levels of intermittent renewables.

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.

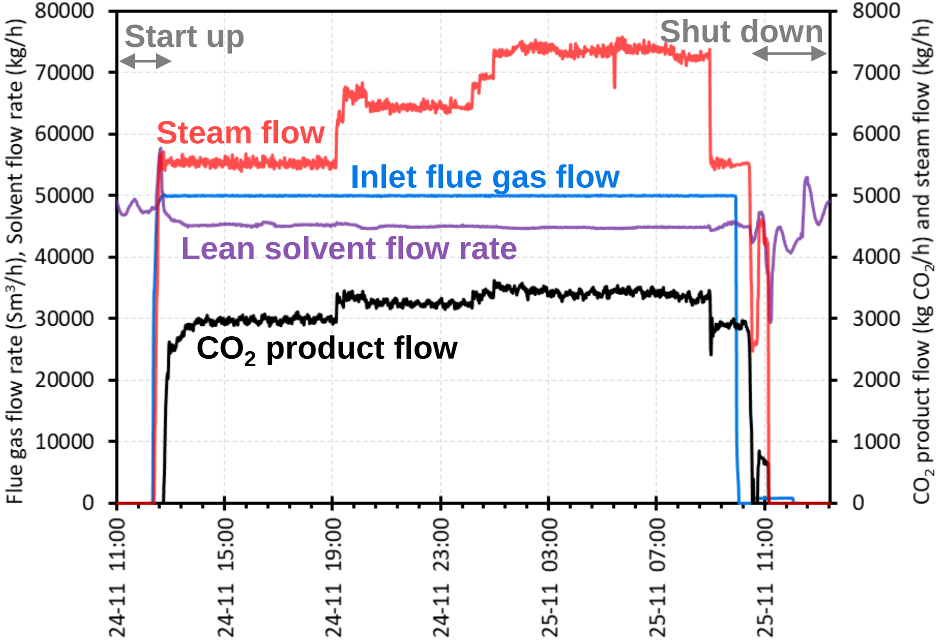
Hot start-up and shut down with 53 m³ solvent inventory

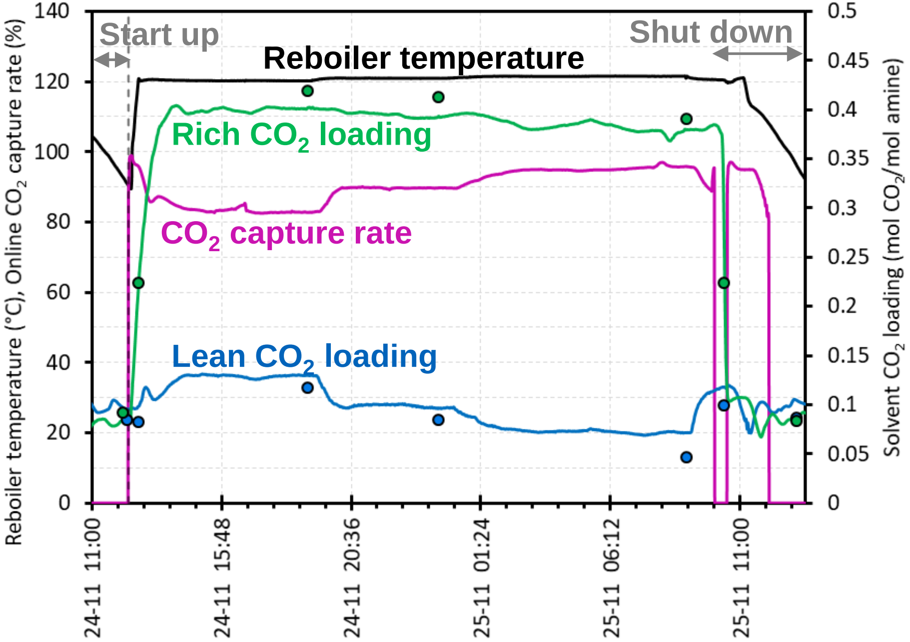


Bui, M. & Mac Dowell, N., under review, Start-up and shutdown protocol for power stations with CO_2 capture, IEAGHG report.

Effect of process dynamics of the capture performance

Hot start-up and shut down with 53 m³ solvent inventory



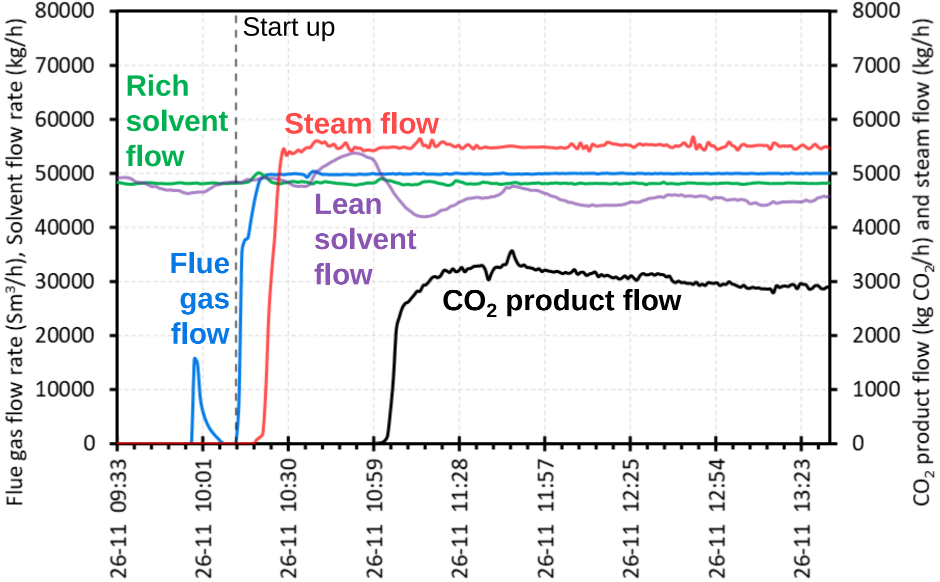


As shown previously, balancing the duration of capture modes is important in ensure capture requirements are met. In the above test, the plant cumulatively captured 90% of the feed CO_2, despite online capture rate varying from 99% to 83%, then increasing to 90% and 96%.

Bui, M. & Mac Dowell, N., under review, Start-up and shutdown protocol for power stations with CO_2 capture, IEAGHG report.

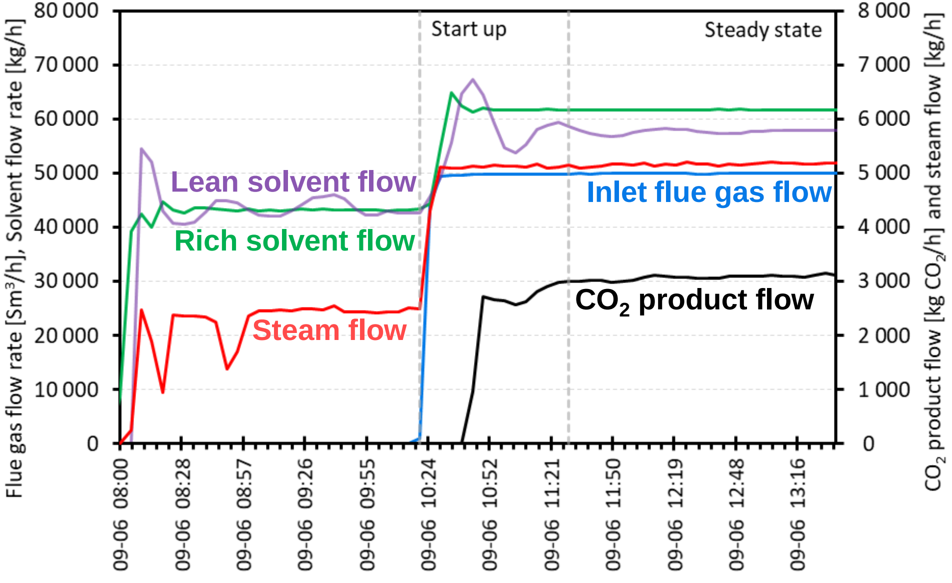
Improving capture performance during start-up

Cold start-up with 42 m³ solvent inventory



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

Cold start-up with preheating and using 45 m³ inventory

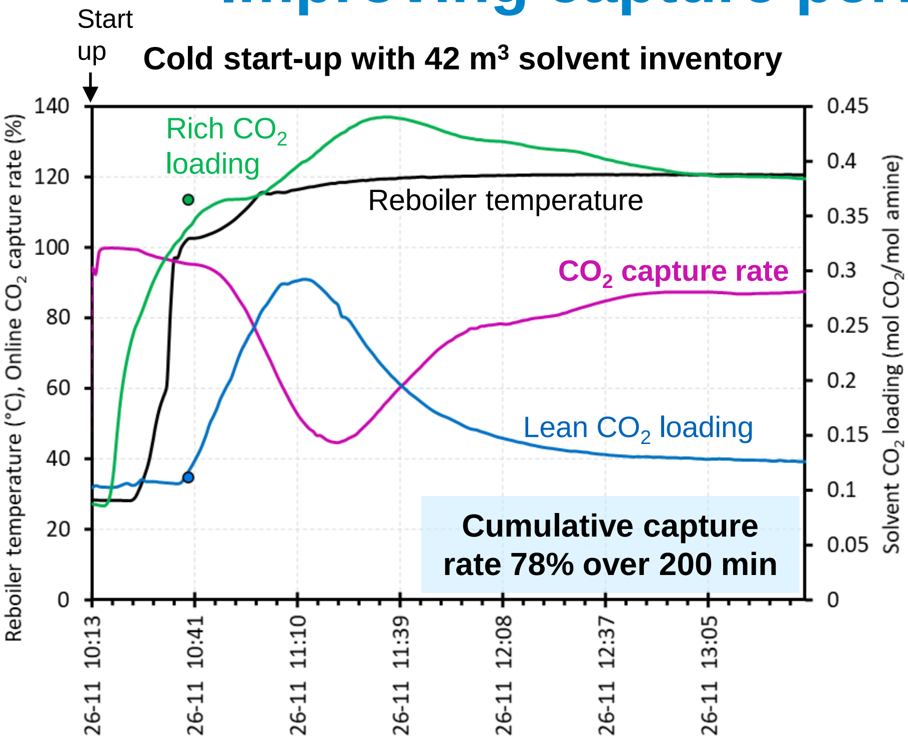


Steam flow started earlier than the flue gas flow rate to simulate "preheating".

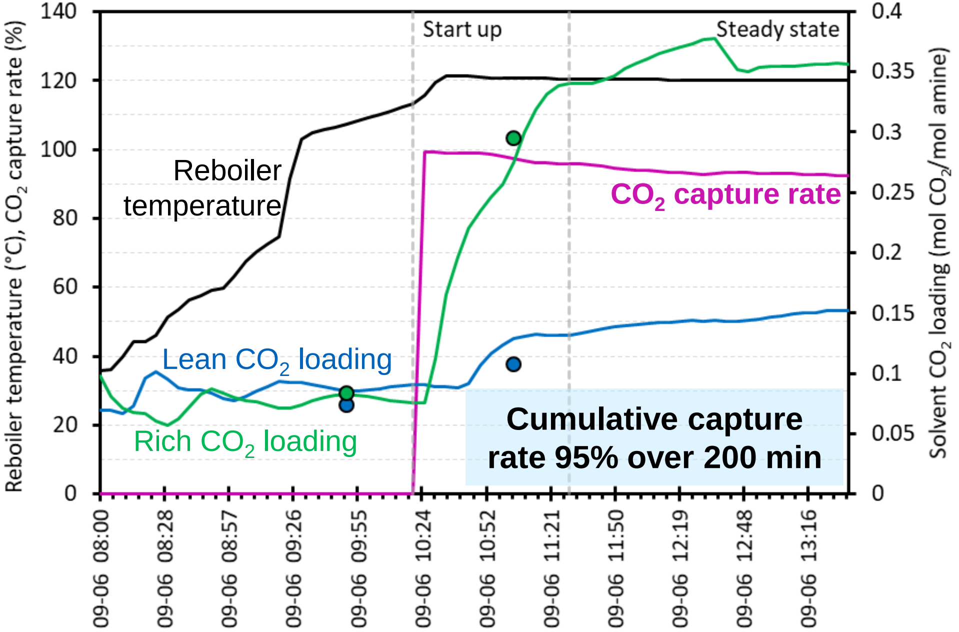
Bui, M. & Mac Dowell, N., under review, Start-up and shutdown protocol for power stations with CO_2 capture, IEAGHG report.

Improving capture performance during start-up

Cold start-up with 42 m³ solvent inventory



Cold start-up with preheating and using 45 m³ inventory



Conventional start-up: Reboiler is not at the set-point temperature at the time FG starts, causing the CO_2 capture rate to drop from 99.8% to 44.6%, before increasing again to 87%.

Start-up with preheating: Reboiler reaches set-point temperature much quicker. The CO_2 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 CO_2 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% CO_2 capture

In countries with net-zero targets, higher CO_2 capture rates of 95% or higher will be essential to reduce the burden on CO_2 removal from the atmosphere (may be more expensive and limited in scale).

We have mainly focused on increasing CO_2 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 CO_2 emissions. The supply chain CO_2 emissions associated with the fuel (e.g., natural gas, coal, biomass) will also have an impact on the actual CO_2 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 CO_2 capture rate in other non-combustion applications for CO_2 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 CO_2 emissions and cumulative CO_2 capture %. This will likely have an impact on regulation and policy for CO_2 emissions from power and industry.