Why 100% capture matters

Professor Mathieu Lucquiaud, UKCCSRC/University of Sheffield

Connah's Quay, 15th April 2026

- Net zero by 2050 is only an interim target
- The end goal is net-negative, with the magnitude of GHG removal yet to be determined
- Capturing (as close as possible to) all CO_2 from fossil fuel use
  - initially creates 'space' for harder-to-abate sectors in the 2030-2040s
  - displaces the deployment of more expensive GHG removal technology in the 2040s and beyond
- The long-term direction of travel for any CO_2 capture technology is ***'100 percent, all the time'***
- Current tranche of (UK) CCS projects – 95% capture, but…

GOV.UK

https://www.gov.uk/guidance/post-combustion-carbon-dioxide-capture-best-available-techniques-bat

Home > Environment > Climate change and energy > Energy efficiency

Guidance

Post-combustion carbon dioxide capture: emerging techniques

Emerging techniques on how to prevent or minimise the environmental impacts of post-combustion carbon dioxide capture.

From: **Environment Agency**

Published 2 July 2021

Last updated 27 March 2024 — See all updates

3. PCC plant design and operation

3.1 Purpose

The purpose of the PCC plant is to maximise the capture of CO_2 emissions for either use or secure geological storage.

You should aim to design your plant to achieve a CO_2 capture rate of at least 95% during normal operating conditions, although operationally this can vary, up or down.

You will need to justify proposing a design CO_2 capture rate of less than 95% as an annual average of all normal operating conditions. You can submit a cost benefit analysis as part of your application.

Department for Business, Energy & Industrial Strategy

Carbon Capture, Usage and Storage

Dispatchable Power Agreement business model summary

https://assets.publishing.service.gov.uk/media/6373993e8fa8f559604a0b8b/ccus-dispatchable-power-agreement-business-model-summary.pdf

The Availability Payment is calculated for each AP Billing Period with the following formula:

$$AP = \sum (AG_i \times \boxed{AC_i \times NDC} \times APR_i) + TSCC + TSNC$$

Term	Definition
AC_i	Availability of Capture applicable to Settlement Unit i (%)
NDC	Net Dependable Capacity (MW)

- If capture rate increases by 1%, and
- Net power output decreases by less than 1%, then
- Payment increases in the DPA business model

- <u>The DPA may incentive to increase capture rates operationally</u>

Ultra high CO_2 capture rates in CCGTs

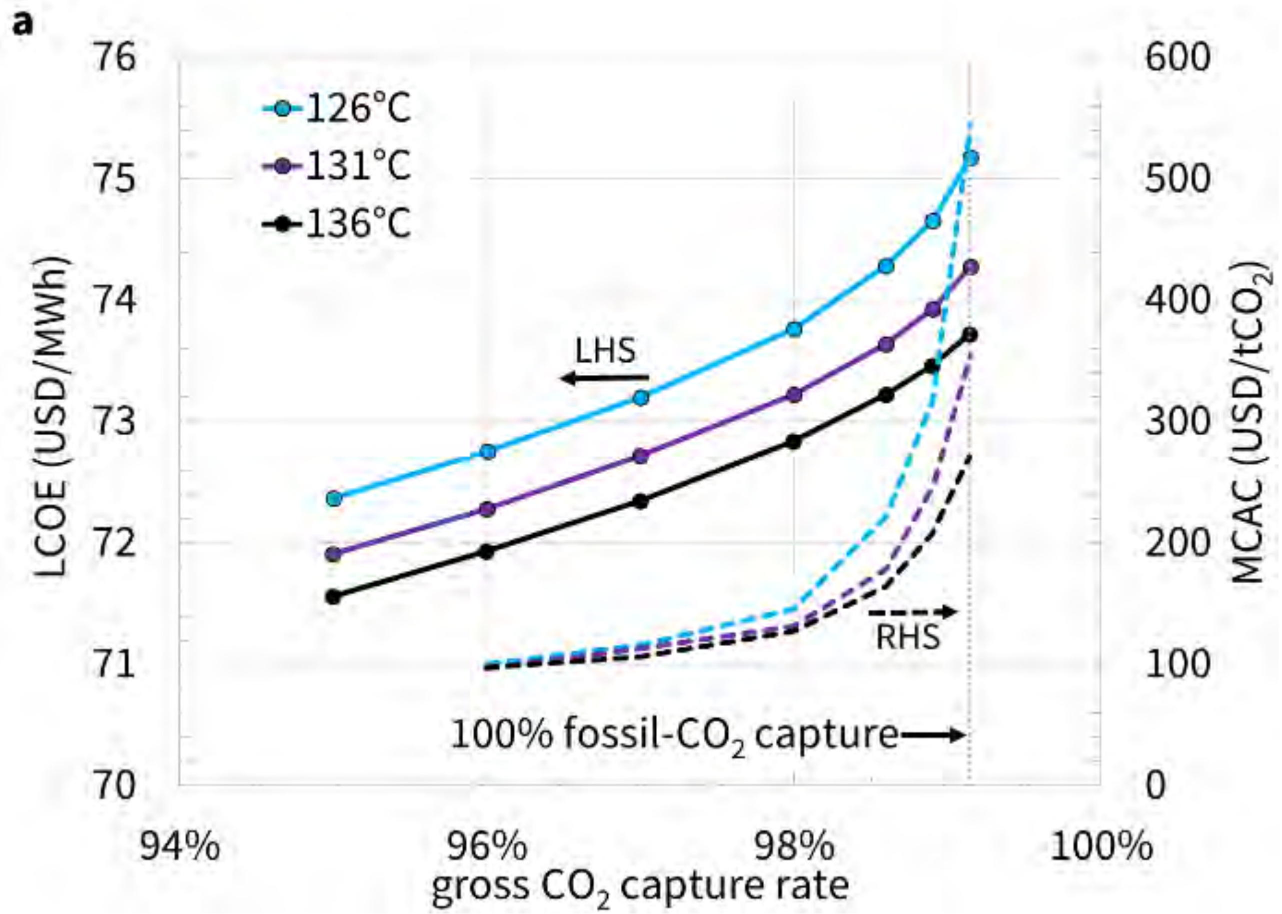


Figure 6. Impact of CO_2 capture rate on LCOE and MCAC with optimal absorber bed height. LCOE (solid lines, LHS) and MCAC (dashed lines, RHS) versus CO_2 capture rate for 1x1 H-class CCGT with regenerator reboiler temperature of 126°C and lean solvent CO_2 loading 0.15 mol_{CO2}/mol_{MEA} (blue lines), 131°C and 0.13 mol_{CO2}/mol_{MEA} (purple lines), and 136°C and 0.11 mol_{CO2}/mol_{MEA} (black lines). Absorber bed length adjusted to achieve design CO_2 capture rate with optimal rich solvent CO_2 loading. 3 absorber beds with solvent intercooling between each bed

What is the 'right' capture rate?

Trade-off between the Marginal Cost of CO_2 Avoided (MCAC) of a CCGT and other forms of CO_2 abatement or greenhouse gas removal in the energy system

H-Class CCGT with 35%wt MEA

2025 \$, US based project costs, construction and fuel prices – using the NETL methodology

Cownden, R., Gibbins, J., Lucquiaud, M. (2026) Cost-effective ultra-high CO_2 capture rates for combined cycle gas turbines with monoethanolamine solvent, In preparation

How is capture rate defined in the DPA business model?

Achieved CO_2 Capture Rate

The Achieved CO_2 Capture Rate is calculated for each AP Billing Period by considering the emissions during the AP Billing Period and the CO_2 sequestered into the T&S Network during the AP Billing Period, with all emissions and CO_2 sequestered during any T&S Capture Outage Relief Event excluded from the calculation. This is calculated with the following formula:

$$ACR_{ph} = \frac{CO2_{exp} - CO2_{exp_{CORE}}}{CO2_{gen} - CO2_{gen_{CORE}}}$$

Term	Definition	Source
ACR_{ph}	Achieved CO_2 Capture Rate (%)	Calculated
$CO2_{exp}$	AP Metered CO_2 Output (over an AP Billing Period) (tCO_2)	Metered on entry to T&S network at the CO_2 Delivery Points
$CO2_{expCORE}$	AP Metered CO_2 Output with Capture Outage Relief Event (tCO_2)	Metered on entry to T&S network at the CO_2 Delivery Points
$CO2_{gen}$	AP Calculated CO_2 Generated (over an AP Billing Period) (tCO_2)	Calculated from Total Metered Fuel Consumption and the Fuel Composition using JEP[22] methodology
$CO2_{genCORE}$	AP Calculated CO_2 Generated with Capture Outage Relief Event (over an AP Billing Period) (tCO_2)	Calculated from Total Metered Fuel Consumption and the Fuel Composition using JEP methodology

Table 8: Definition of terms in the Calculation of Achieved CO_2 Capture Rate formula.

- Capture rate calculations is the ratio of two large numbers
- Not fit for purpose for ultra high capture rates
- Absorber CO_2 exit concentration measurement ?
- Capture rate is limited to 100%
- CCGTs may need to achieve capture rates >100% in the future
  - For short periods of time for averaging capture rates
  - For long periods of time if/when Direct Air Capture is integrated with amine capture

https://assets.publishing.service.gov.uk/media/6373993e8fa8f559604a0b8b/ccus-dispatchable-power-agreement-business-model-summary.pdf

Ultra high capture for Waste to Energy with CCS – WECCS

95% capture – regulatory target for UK WECCS plants

UK Waste Industrial Capture contracts

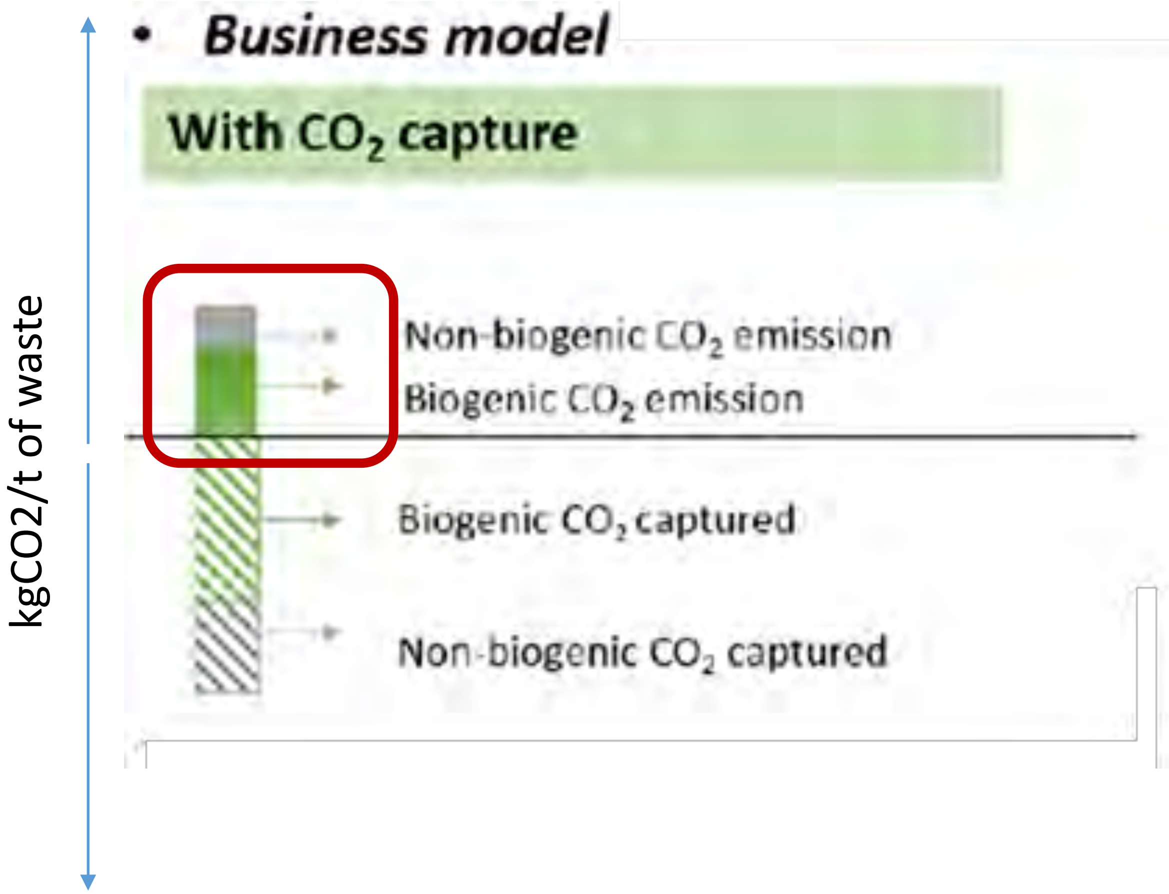
- Maximum capture rate of 100%
- Greenhouse Gas Removal – 'Restrict and Review'

Ultra-high capture: key considerations

- 5% residual emissions: are they fossil, biogenic or based on fuel compositions?
- If increasing capture rate beyond 95%

-> Additional Greenhouse Gas Removal, at a marginal cost likely to be lower than other forms of premium GGR

-> Maximise value to energy system and/or rate of return



High capture rates for net zero: experience from the COGENT project tests in China

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COGENT – Capture Operation with Greater Economy for Net-zero Targets

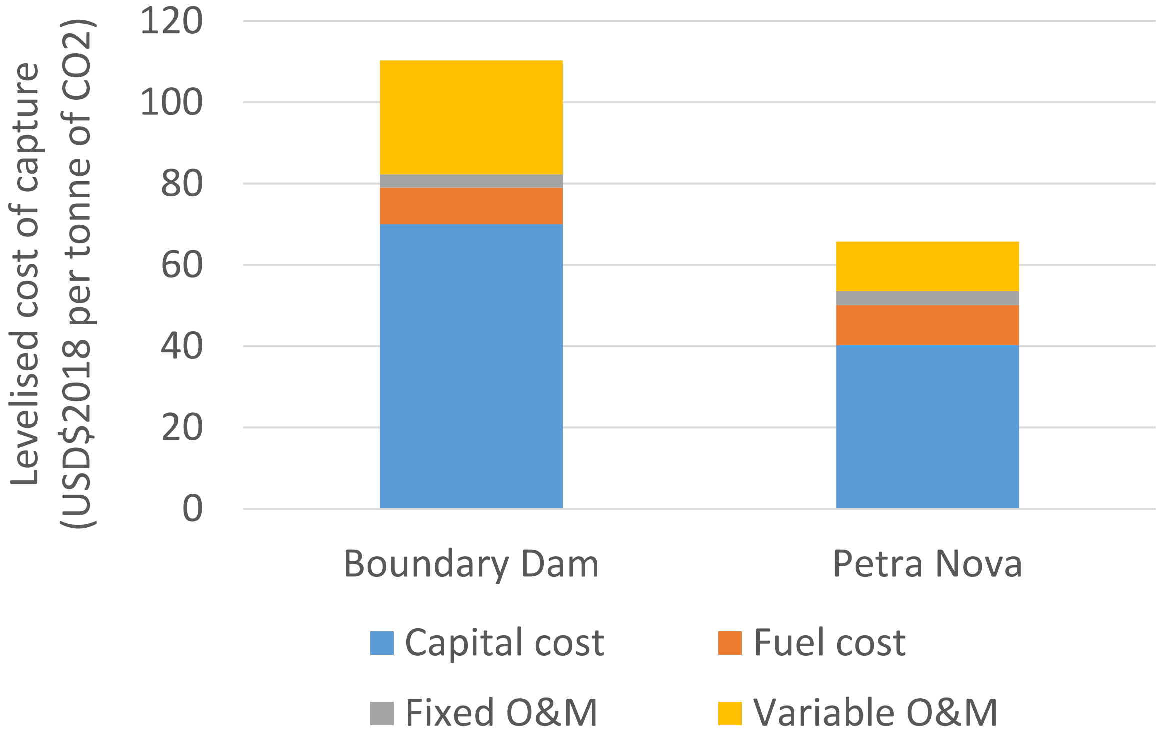
STRETCHER - System Tuning for Regenerator Efficiency and Target Capture with High Exit Rich

Based on projects funded by FCDO, DESNZ, building on previous UKCCSRC/EPSRC and University of Sheffield projects

NOTE ON THE USE OF MEA: Reported capture costs for actual PCC on coal power plants using proprietary solvents show higher variable O&M costs than additional fuel costs

(GCCSI (2019) *Global Status of CCS Report: 2019.* https://www.globalccsinstitute.com/resources/publications-reports-research/global-status-of-ccs-report-2019/)

The Global CCS Institute has reported costs for capture at the two large-scale power plant PCC projects that have been built, showing the relative weighting of different factors that have been observed in practice.



Proprietary solvents reported as being used in these projects:

Boundary Dam 3: Cansolv DC-103
https://www.carboncapturejournal.com/news/saskpower-boundary-dam-project/2775.aspx?Category=allll

Petra Nova: MHI KS-1
http://www.mhi.co.jp/technology/review/pdf/e551/e551032.pdf

'Variable O&M' costs are likely to be predominantly for solvent management and replacement. Results based on 8% discount rate, 30 years project life, 2.5 years construction time, capacity factor of 85%. Cost data normalised to 2017 values. Stated accuracy range: Boundary Dam and Petra Nova: -10% to +15%.

For Boundary Dam, which captures less than 1MtCO_2/yr, annual costs for solvent replacement alone were stated by the SaskPower chairman as $17.3M in 2015, $14.6M in 2016 (SaskPower, 2016) and reported to a government committee as $13.6M in 2017 (SaskPower, 2018), against initially-predicted costs of $5M. These solvent replacement costs would be consistent with the level of variable operation and maintenance (O&M) costs above.

SaskPower (2016) *A Word from the President on Smart Meters and Carbon Capture and Storage*, Blog on SaskPower web site, December 16, 2016.

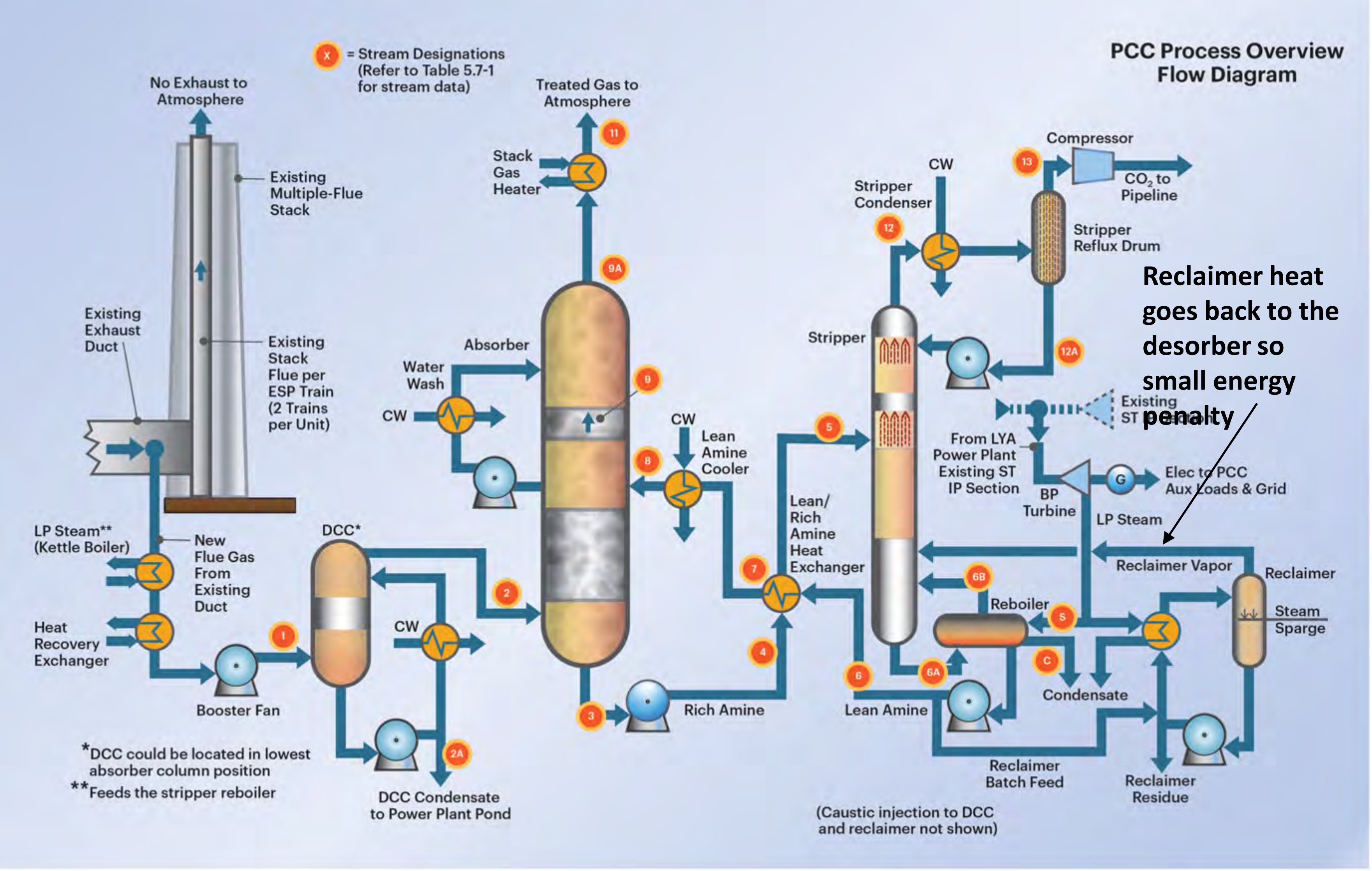
SaskPower (2018) *Letter to Herb Cox, Chairman, Standing Committee on Crown and Central Agencies, Government of Saskatchewan*. http://docs.legassembly.sk.ca/legdocs/Legislative%20Committees/CCA/Tableddocs/CCA%2061-28%20SaskPower%20Responses%20to%20questions%20raised%20at%20the%20June%2027,%202018%20meeting.pdf

NOTE ON THE USE OF MEA: MEA can be thermally reclaimed very effectively and is cheap

- Retrofit study for a brown coal power plant in Australia

Bechtel (2018) for CO2CRC, Retrofitting an Australian Brown Coal Power Station with Post-Combustion Capture, https://ukccsrc.ac.uk/wp-content/uploads/2022/10/Retrofit-Main-Report-Final-Final-in-CO2CRC-webpage.pdf

- Continuous reclaimer venting into desorber to recover thermal energy
- Typically will reclaim one inventory volume in a period of between one week to one month
- Can reject >99% of impurities in simple reclaimer with heat recovery – not possible with blends
- Reclaimer waste may be usable for SCR



Reclaimer heat goes back to the desorber so small energy penalty

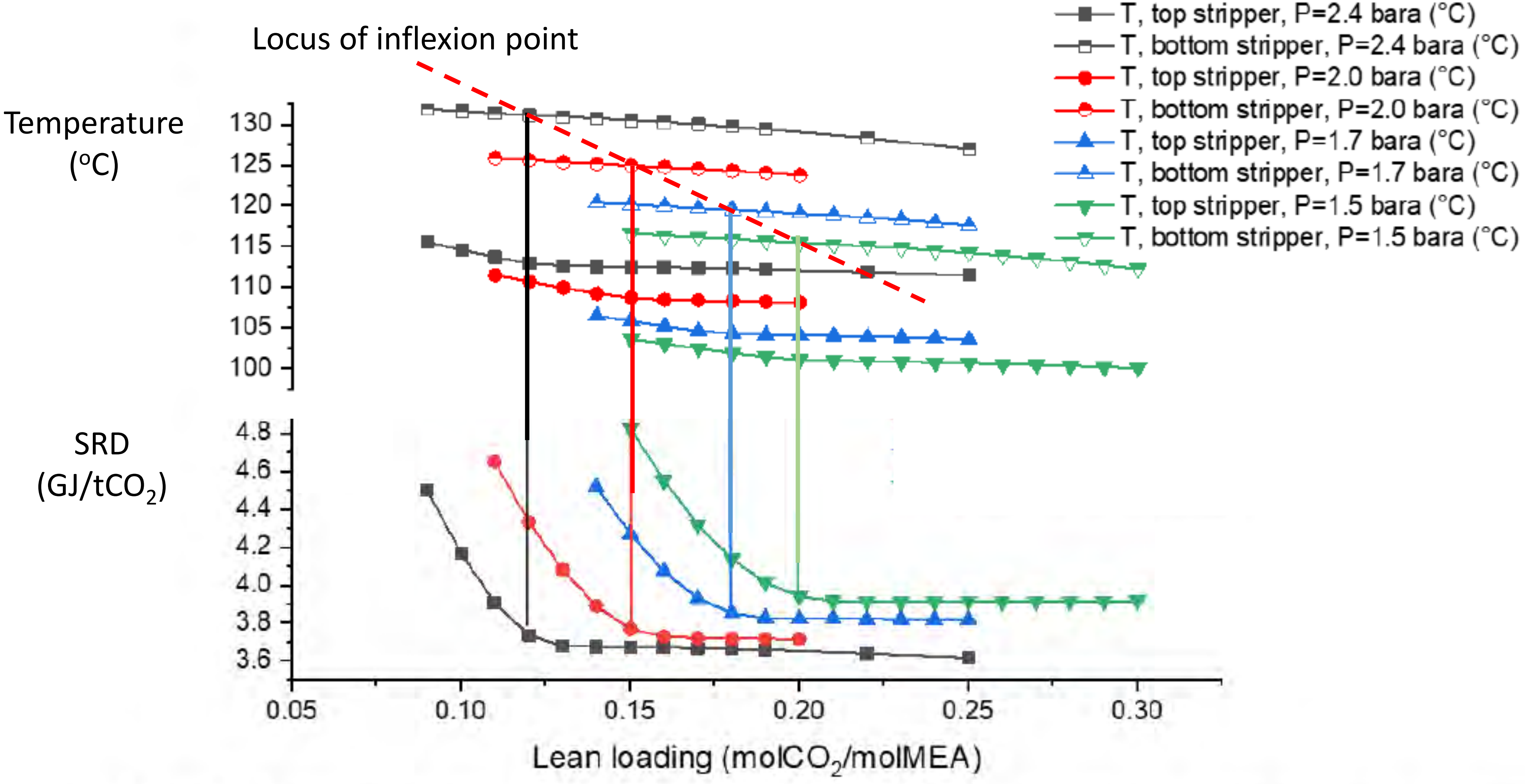
Principles for obtaining ultra-high capture rates:

1. **Produce the lowest possible lean loading without wasted energy** for a given desorber pressure (and hence temperature range) by operating at the **desorber inflection point**.

2. **Use the lean solvent flow rate that gives the optimum combination of capture rate and rich loading** – and hence specific reboiler duty – for that lean loading, given the **absorber corner** constraints.

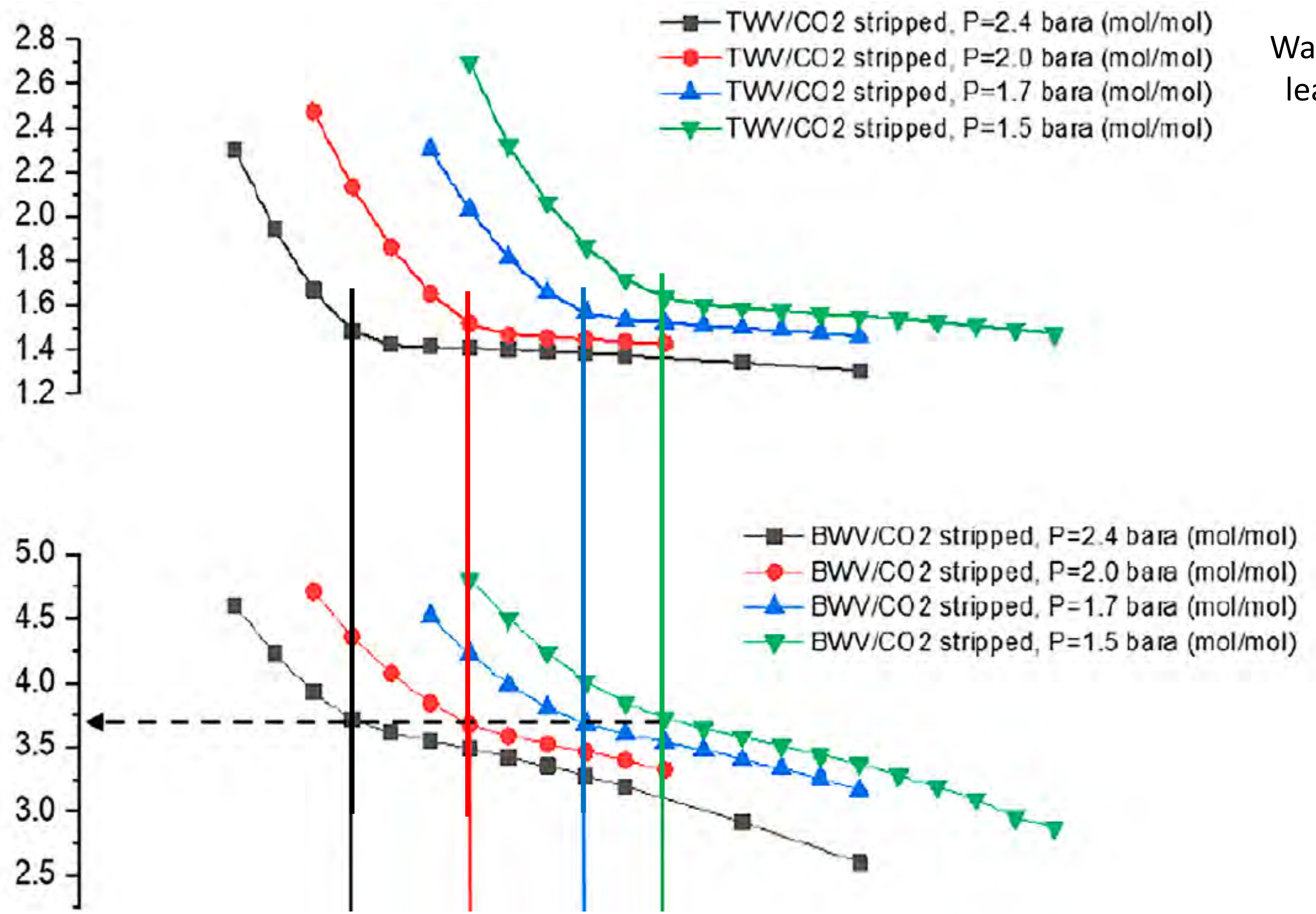
3. Use **lean and rich solvent storage** to allow the desorber and absorber to be operated with the most rapid possible feedback and so be optimised independently in the short term, while obviously still also balancing in the long term.

The inflection point occurs when the specific reboiler duty (SRD) starts to increase rapidly due to water vapour 'breakthrough'. The desorber column exit temperature starts to go up faster than the reboiler temperature.



Michailos & Gibbins, 2022, https://www.frontiersin.org/articles/10.3389/fenrg.2022.866838/full

As the lean loading decreases the water vapour/CO_2 ratio out of the reboiler rises but until the inflection point all of this water vapour can be usefully condensed in the desorber packing.



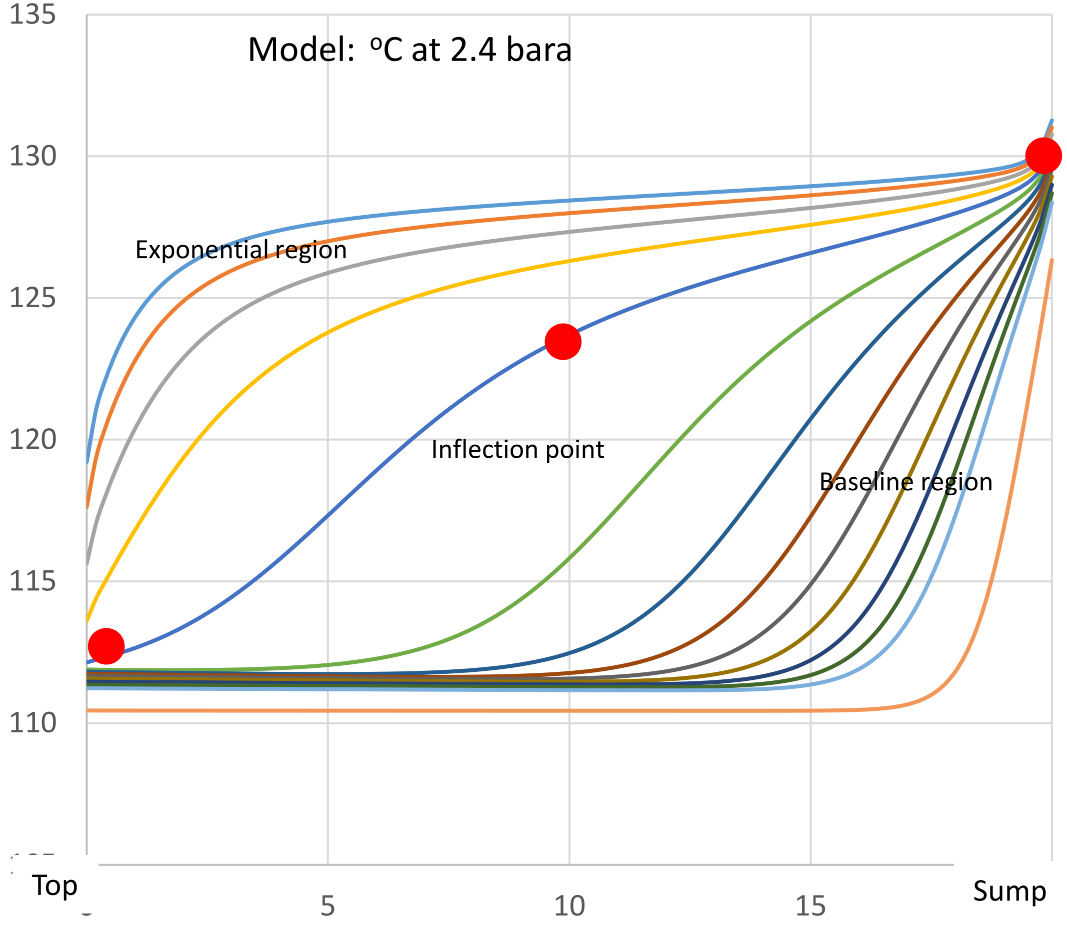
Water vapour/CO_2 ratio leaving the top of the desorber packing

Water vapour/CO_2 ratio leaving the reboiler

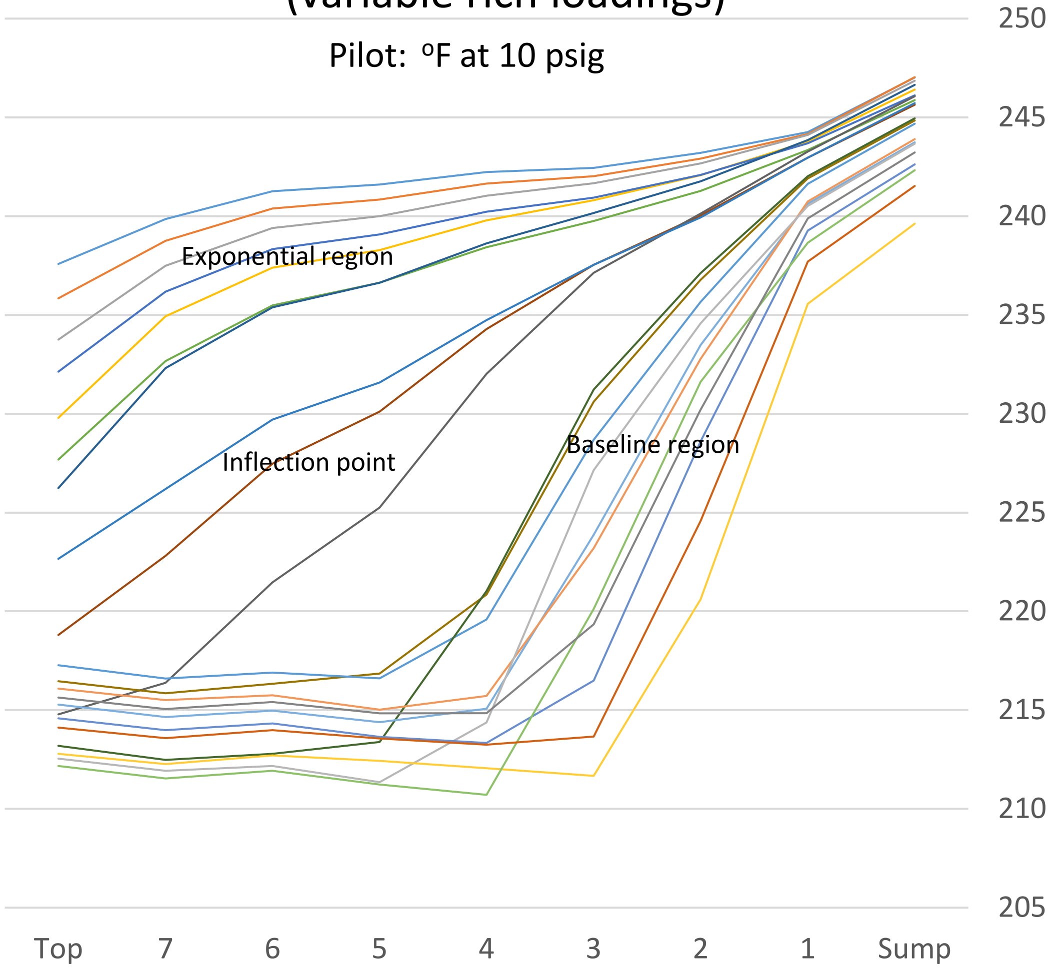
Michailos & Gibbins, 2022, https://www.frontiersin.org/articles/10.3389/fenrg.2022.866838/full

The phenomena that cause the inflection point are visible in the desorber column temperature profile

Modelled desorber internal temperature trends (constant rich loading)



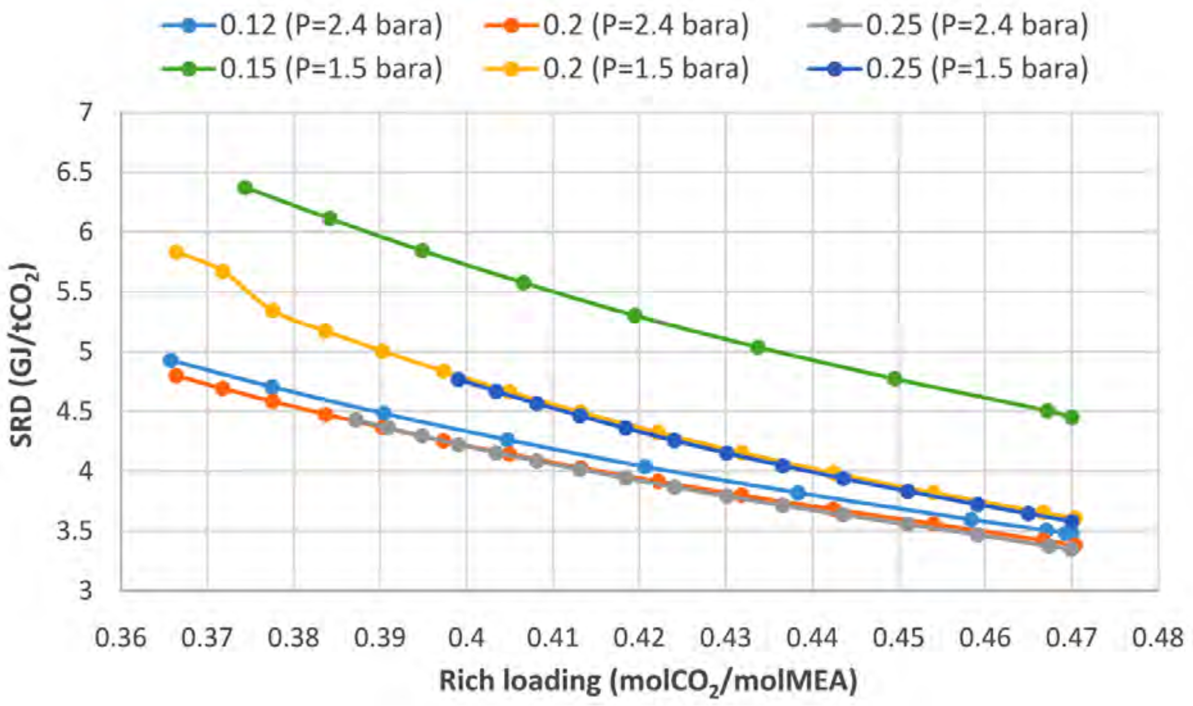
Stripper internal temperature trends observed on the National Carbon Capture Center's 10tCO_2/day pilot plant (variable rich loadings)



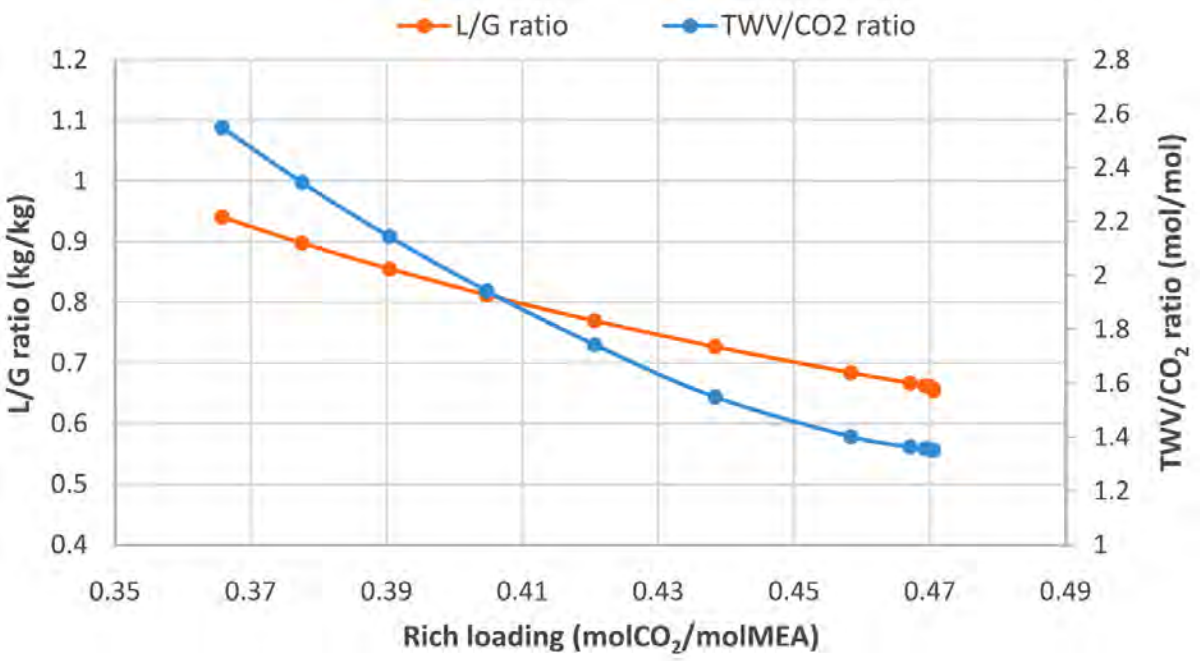
https://www.linkedin.com/pulse/stretcher-method-optimising-amine-post-combustion-capture-jon-gibbins

https://www.linkedin.com/pulse/amine-desorber-temperature-profile-key-optimising-net-zero-gibbins

SRD is insensitive to lean loadings down to the inflection point, but SRD is always sensitive to rich loading



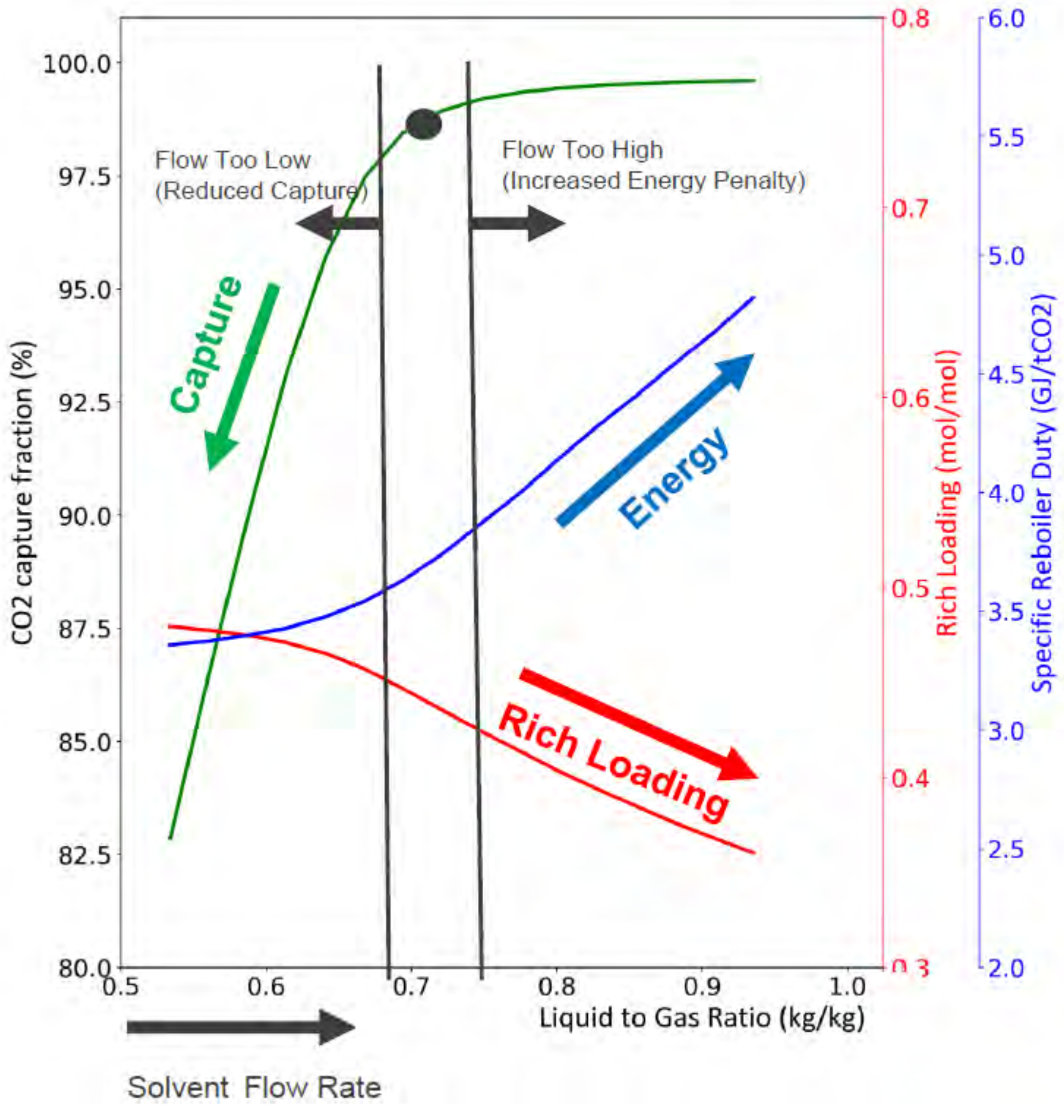
Effect of rich loading and desorber pressure on the specific reboiler duty for different lean loadings of 0.12 (only for desorber pressure of 2.4 bara), 0.15 (only for desorber pressure of 1.5 bara), 0.2 and 0.25 $molCO_2/molMEA$.

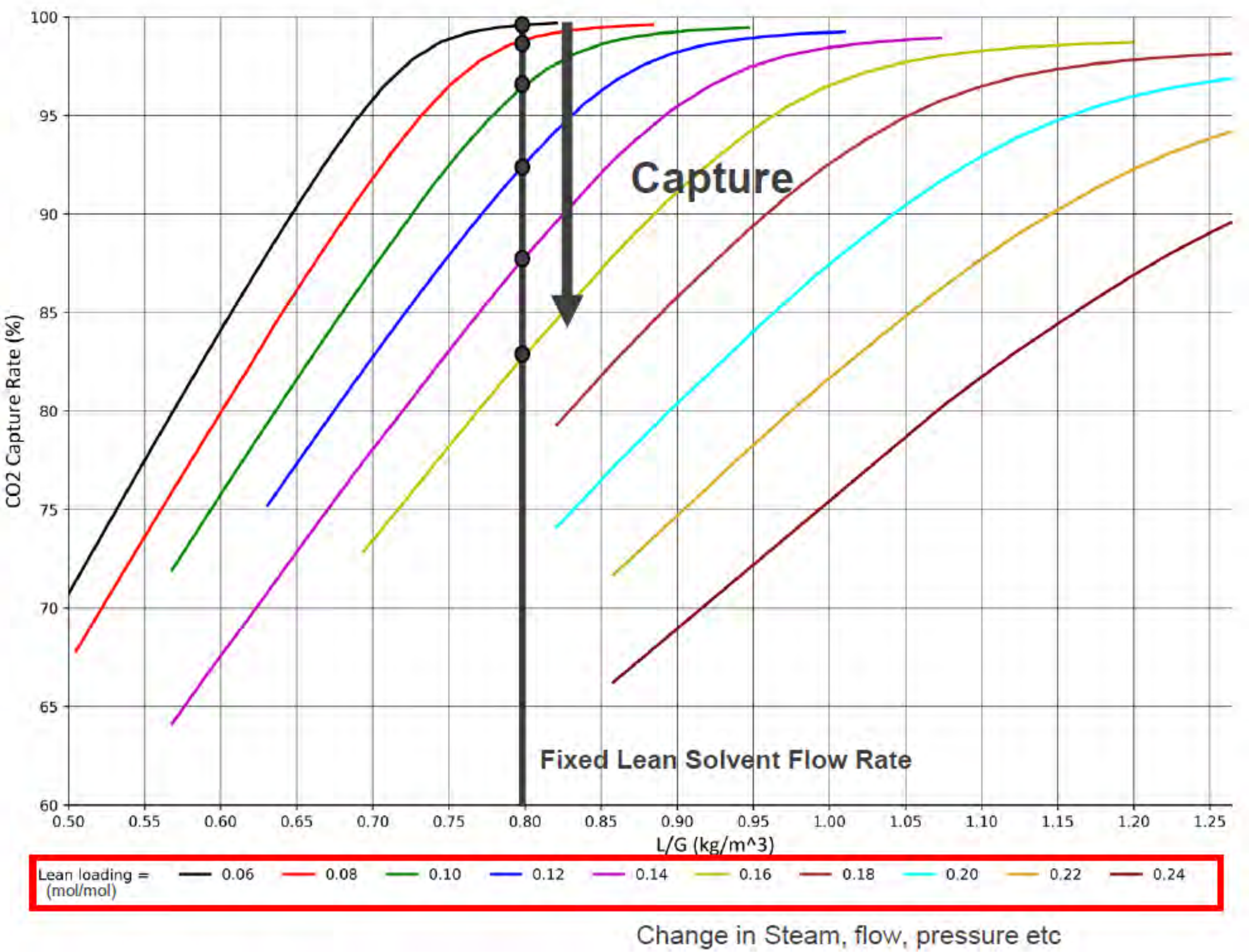


L/G ratio and TWV/CO_2 ratio as a function of rich loading. Lean loading is 0.12 $molCO_2/molMEA$ and desorber pressure is 2.4 bara.

Michailos & Gibbins, 2022, https://www.frontiersin.org/articles/10.3389/fenrg.2022.866838/full

The absorber corner is the region where, at a given lean loading and packing height, the capture rate and SRD are co-optimised by controlling solvent flow to achieve a High Exit Rich (loading)





FCDO CLEEN Project:

COGENT – Capture Operation with Greater Economy for Net-zero Targets

中英（广东）CCUS中心
UK-China (Guangdong) CCUS Centre

The University Of Sheffield. Energy Institute

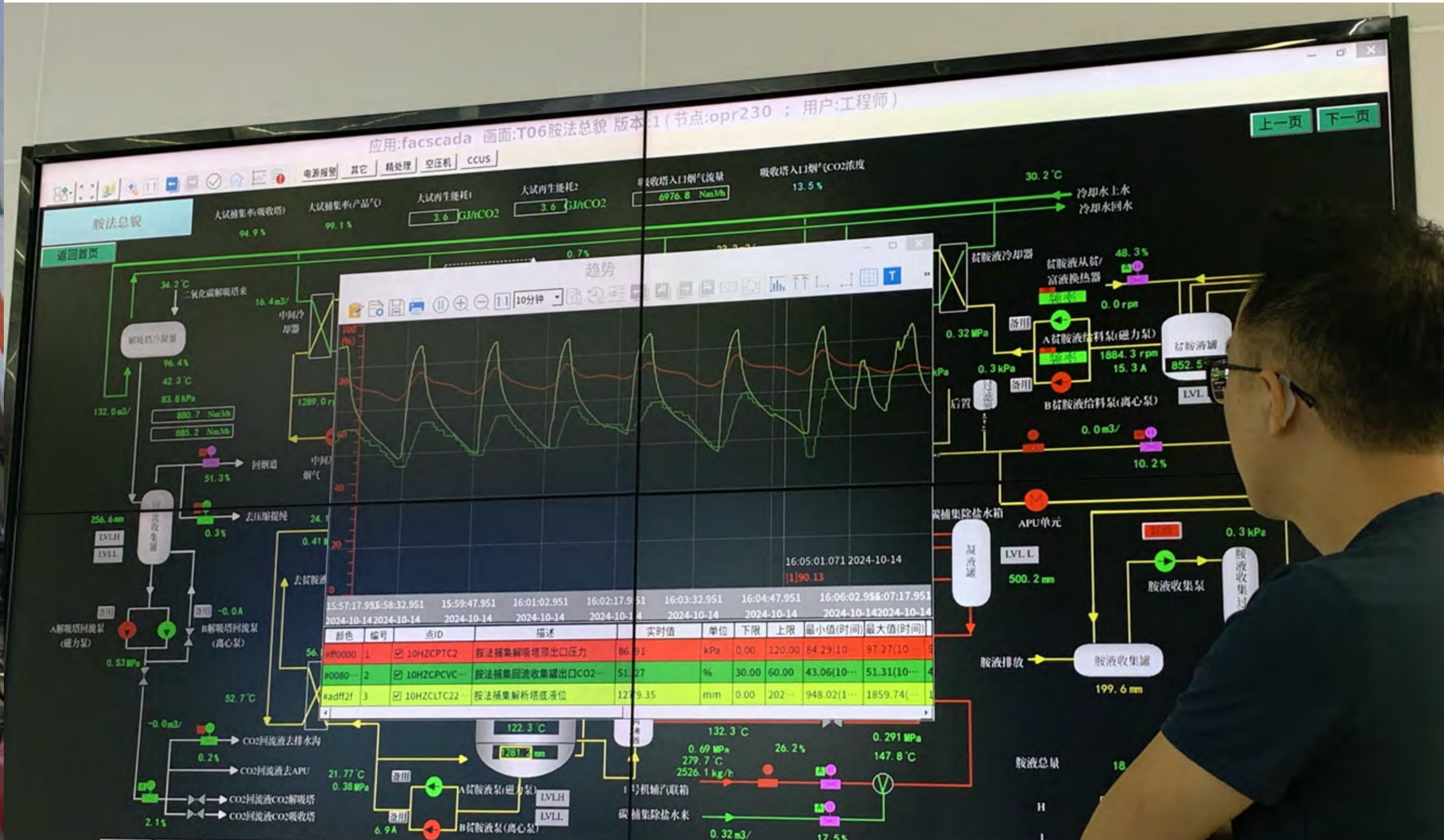
UKCCS RESEARCH CENTRE

GD UK-China CCUS Centre

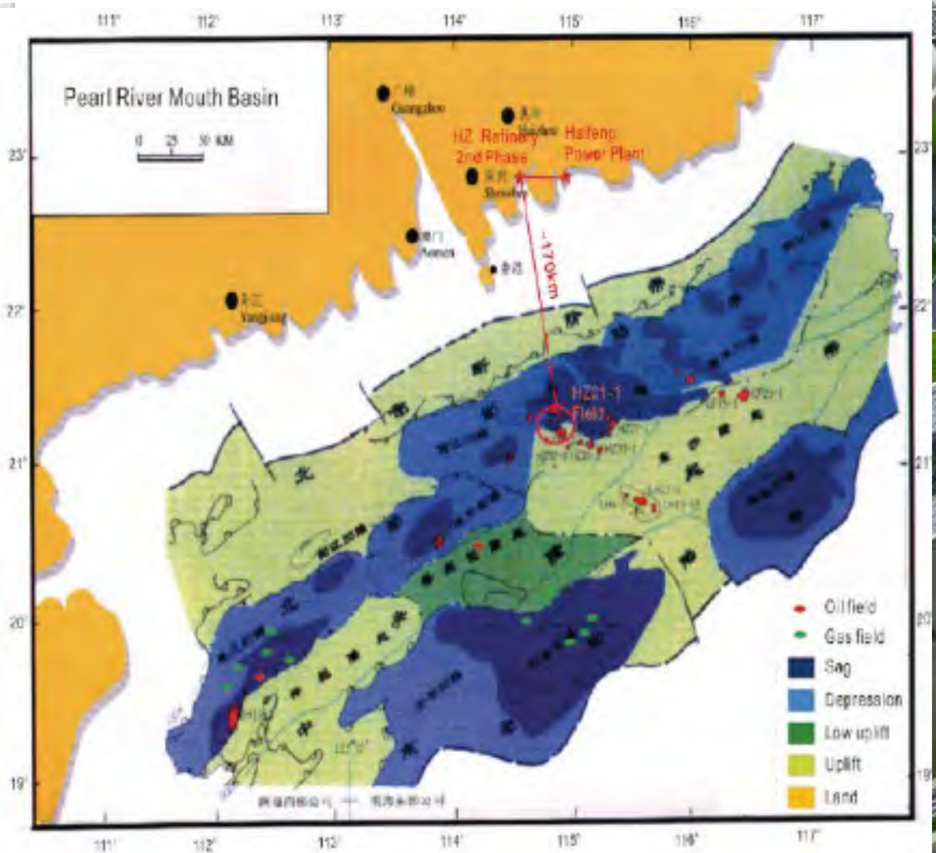
Guangdong Carbon Capture Test Platform – ~ 40tCO_2/day in tests

University of Sheffield/UKCCSRC

Project report here: https://ukccsrc.ac.uk/research/flexible-funding/flexible-funding-2021/prof-jon-gibbins-university-of-sheffield



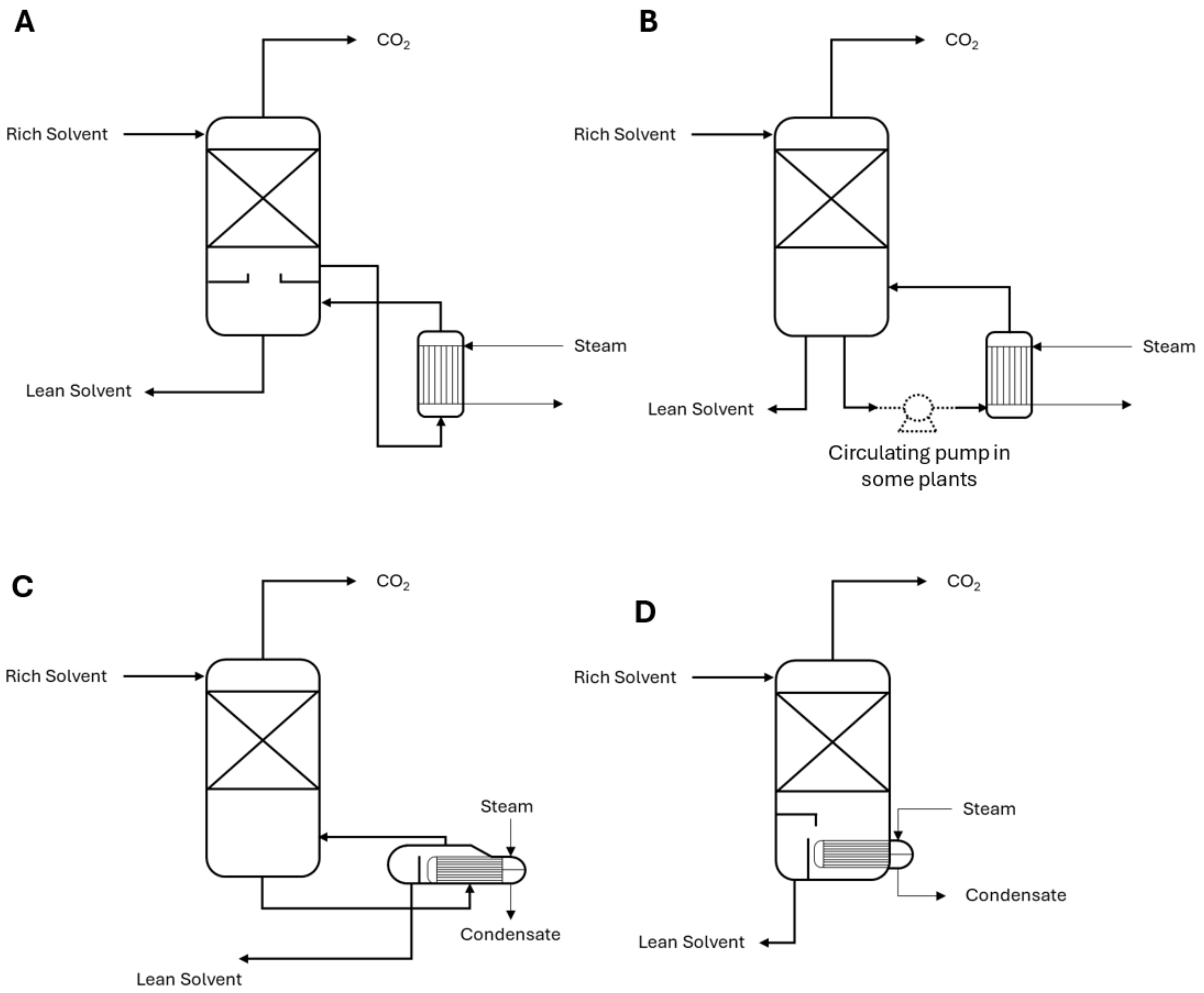
China Resources Haifeng Power Plant



Guangdong Carbon Capture Test Platform

A visit in August 2024 to discuss the theory behind high CO_2 capture rates with the Haifeng capture plant team, familiarize the GDCCUS/UKCCSRC team with the Haifeng pilot plant and plan the test campaign.

The once-through reboiler at Haifeng is an industry standard on commercial plants but is unusual for a pilot plant.



Once-through thermosyphon and other reboilers – diagrammatic arrangement

(reflux arrangements at the top of the desorber, integrated thermal reclaimers etc. have been omitted for simplicity)

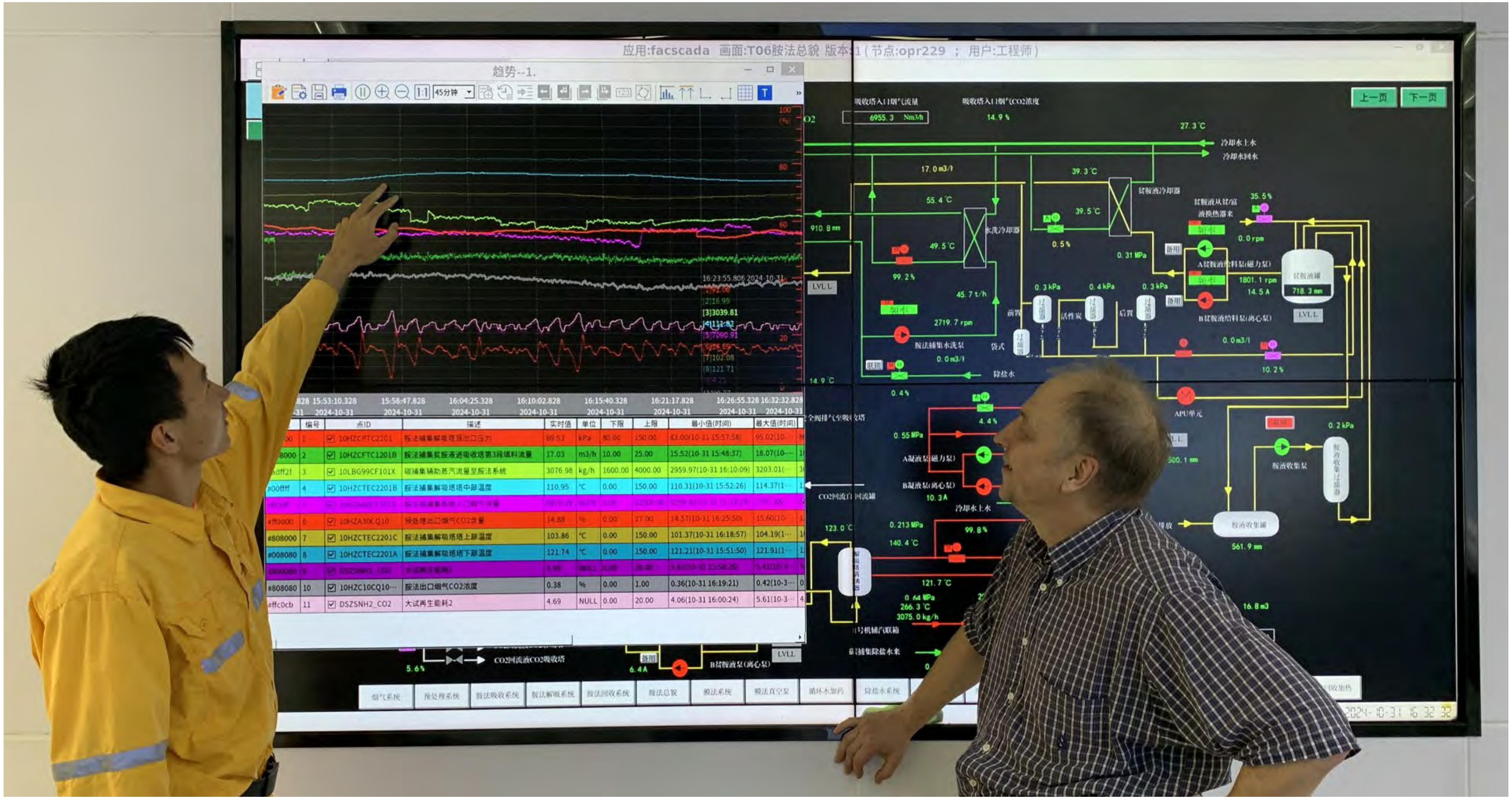
A: Once through thermosyphon;

B: Natural or pumped circulation thermosyphon

C: Natural or pumped circulation thermosyphon with external kettle reboiler

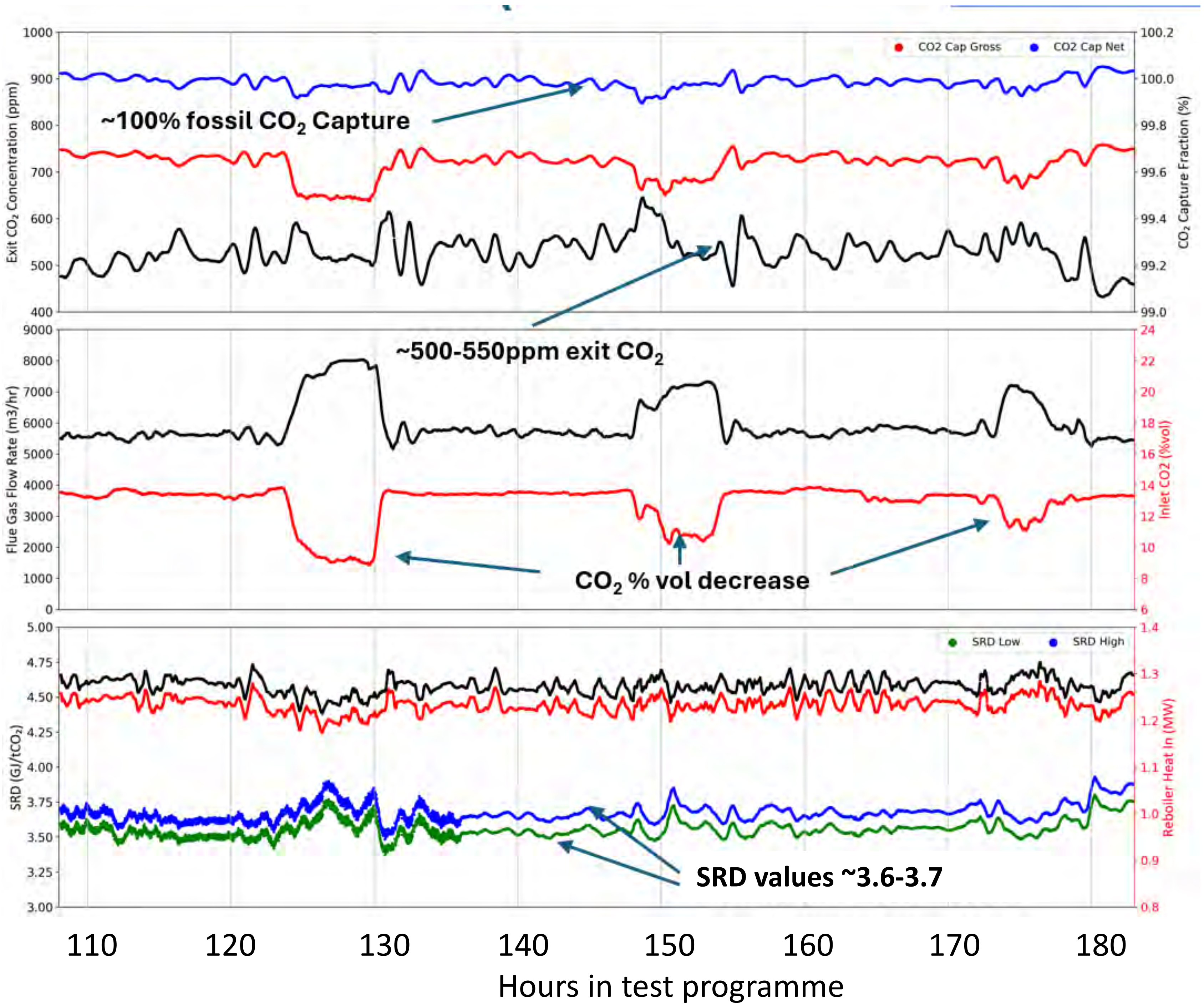
D: Integrated kettle reboiler

Initial testing in October 2024 confirmed the principles for desorber and absorber control at high capture rates and demonstrated 98% capture rates with low reboiler energy, but the performance was limited by the desorber pressure that could be used at that time, 1.9 bara



In recent tests in December 2025 the desorber pressure was increased to 2.4 bara, giving a lower lean loading at the inflection point and that allowed a capture rate of ~100% of the fossil CO_2 to be achieved with reasonable SRD values.

The plant was operated under continuous control for a period of 75 hours.



Summary

- The theoretical principles for achieving up to 100% of fossil CO_2 capture that were developed in modelling work in the UK have been demonstrated in pilot testing in China at ~40 tCO_2/day scale
- The realistic once-through thermosyphon at the Haifeng pilot plant was essential to apply effective control – this type of equipment is standard for full-scale plants but not widely used on pilot plants elsewhere
- Next stages include adding air dilution at Haifeng to allow testing at ~4-5% inlet CO_2 concentration to match CCGT flue gases, but the exit CO_2 for 100% fossil capture will be very similar at ~ 500 ppm
- Operation under CCGT start/stop conditions will also be investigated

Longer term plans - Advanced Capture Exemplar (ACE) pilot

- Continuous reclaiming for solvent management
- Ultra-low amine and degradation product emissions to atmosphere
- Novel instrumentation for continuous solvent loading and concentration monitoring
- Continuous 100% fossil CO_2 capture using solvent buffer storage