UPCC: ULTRA-HIGH POST-COMBUSTION CO_2 CAPTURE
CO-CAP: COLLABORATION ON COMMERCIAL CAPTURE

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Final project meeting – 13 April 2021

RESEARCH ENGLAND / HEFCE, HEIF (United Kingdom):
KE - QR-POLICY-SPF : UPCC: Ultra-high Post-Combustion CO_2 Capture

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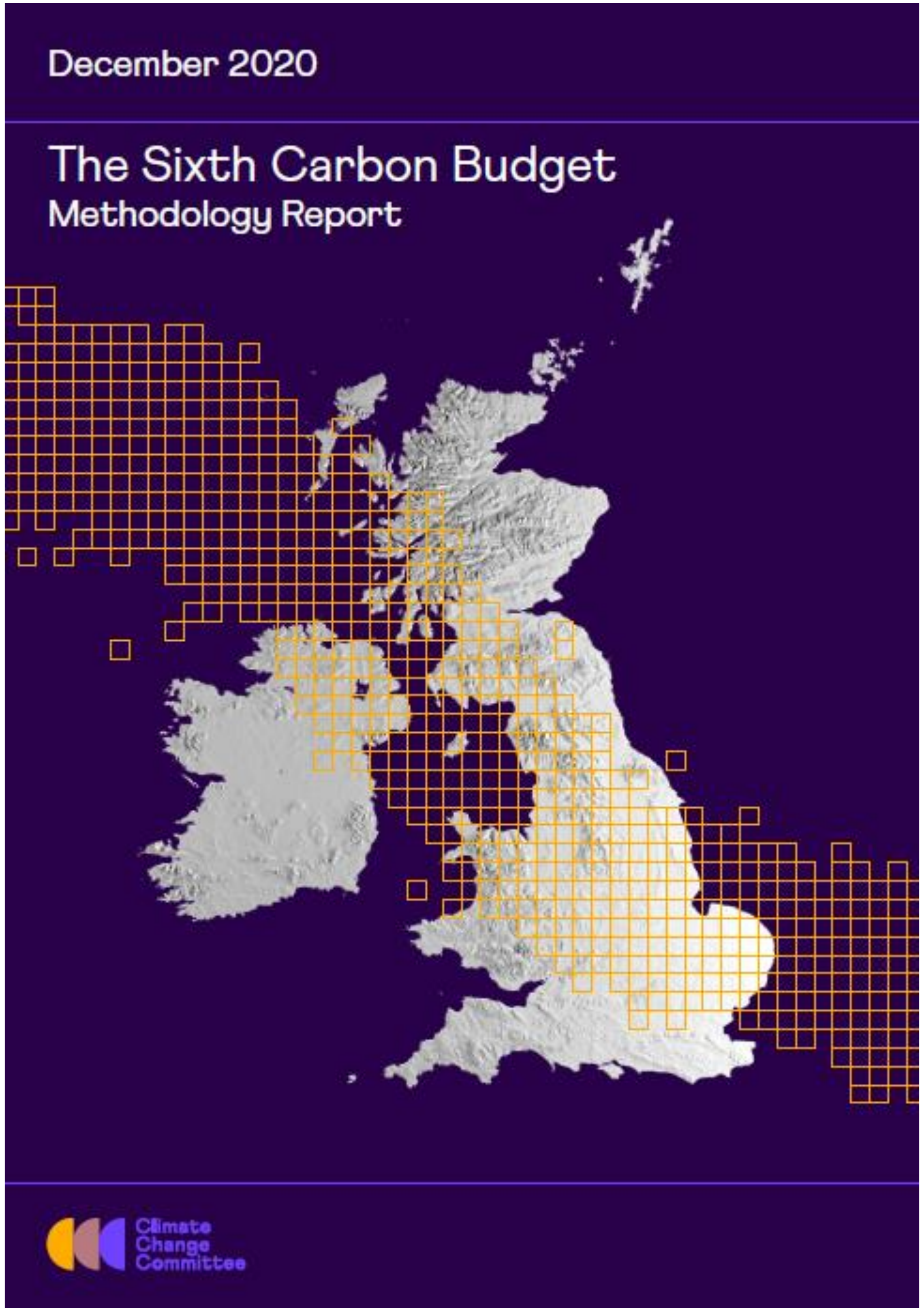
Key points

- Post-combustion amine (PCC) capture of 95% of the CO_2 in the flue gas seems feasible and should become the new design standard (but capture level can be varied during operation – only average long-term emissions matter for the climate)
- Designing new PCC for capture at 95% had wide acceptance at a recent BAT workshop
- Capture up to around 99% also seems viable if designed for
- Higher capture levels always involve higher capital and operating costs, with some trade-offs between them
- There may be resistance from some suppliers who either cannot achieve such high capture levels or, more likely, have not tested them yet
- Nothing is proven until it is tested properly!



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A few small amendments were applied to the deep decarbonisation abatement measures coming from the manufacturing and construction pathways and scenarios from the Element Energy analysis, resulting in a difference between the results reported in the Element Energy report and our results.

In particular, CCS capture rates were adjusted in the period pre-2040 to 90%, from higher rates. A final version of our off-road mobile machinery analysis was also included at this stage.

Box 4.2

Summary of Element Energy analysis and report on Deep Decarbonisation Pathways for UK Industry

We commissioned Element Energy to improve our evidence base and develop pathways for deep decarbonisation from UK industry emissions – currently 110.6 $MtCO_2e$ in total of which 66.2 $MtCO_2e$ is manufacturing and construction, 39.2 $MtCO_2e$ is fossil fuel supply (see Chapter 6) and 5.1 $MtCO_2e$ is energy from waste (see Chapter 10).

- The model used CO_2 capture rate of 95% for CCS in the Balanced Net Zero Pathway, Headwinds, and Widespread Engagement scenarios and a capture rate of 99% in the Widespread Innovation and Tailwinds scenarios. The CCC final results assume capture rates of 90% up until 2040.

Some examples of other published work on 95-99% capture levels

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Fluor examples: '85-95% capture' including on GT flue gases
http://www.zeroco2.no/projects/bellingham
https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.204.8298&rep=rep1&type=pdf

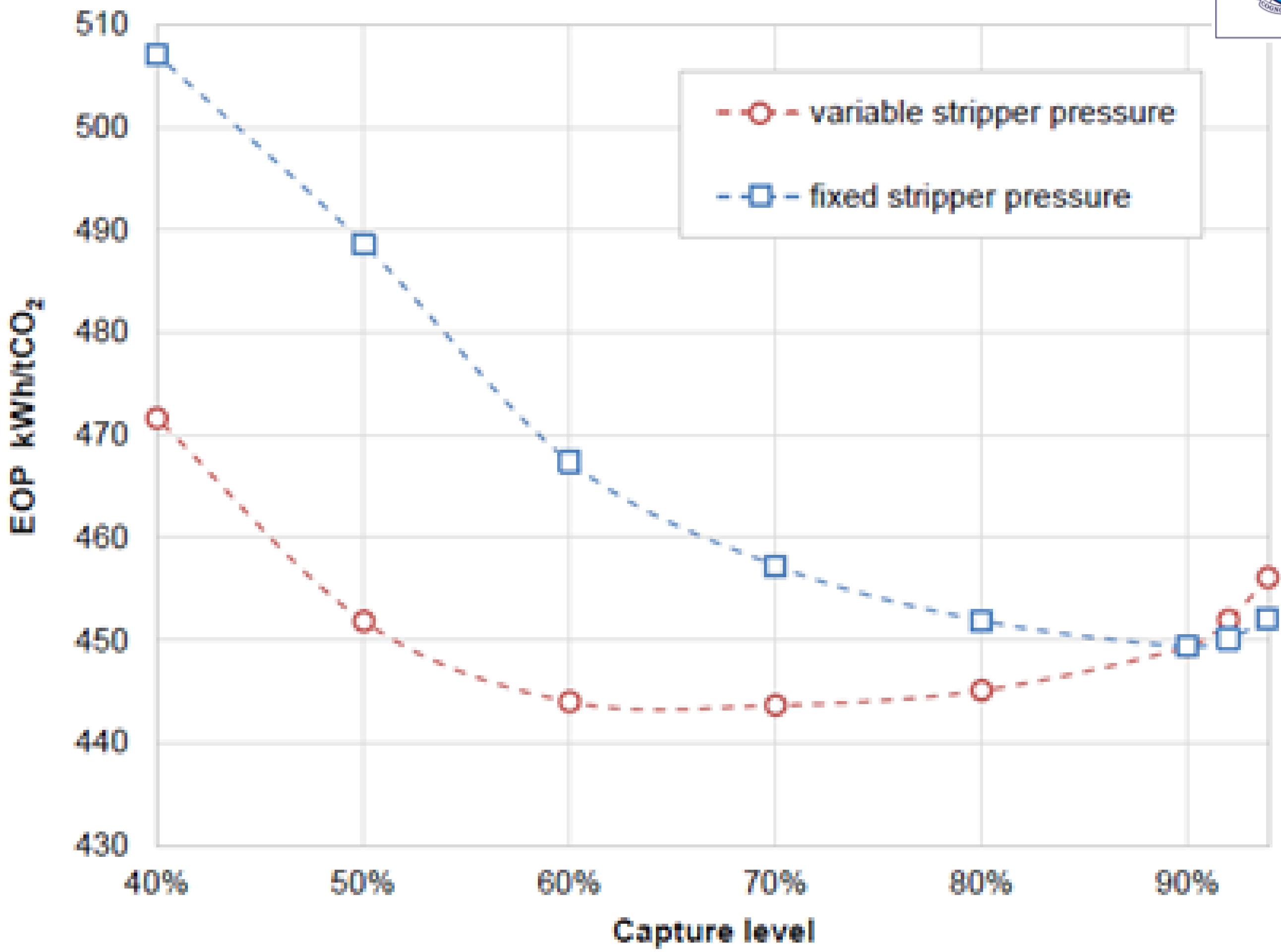
'A 95% CO_2 capture rate was achieved and found to be optimum when studying cases at 85, 90 & 95% CO_2 capture from coal-fired boiler flue gases.' *Application of the Econamine FG Plus process to Canadian Coal-based Power Plant*, Shakir Khambaty, Satish Reddy (Fluor), Robert Stobbs (Saskpower), Clean Coal Session of Combustion Canada Conference, Vancouver, Canada, September 22-24, 2003.
Previously available on https://origin-www.fluor.com/SiteCollectionDocuments/ApplofEFG-ProcesstoCanadianCoal-basedPowerPlant-CombCanadaConf-Sep2003.pdf

MHI example, for up to 99.5% capture on coal flue gases
Takuya Hirata, Tatsuya Tsujiuchi, Takashi Kamijo, Shinya Kishimoto, Masayuki Inui, Shimpei Kawasaki, Yu-Jeng Lin, Yasuhide Nakagami, Takashi Nojo (2020) Near-zero emission coal-fired power plant using advanced KM CDR process™, International Journal of Greenhouse Gas Control, Volume 92. http://www.sciencedirect.com/science/article/pii/S1750583618307527)

IEAGHG study: up to 99.1% capture, including on natural gas
Paul Feron, Ashleigh Cousins, Kaiqi Jiang, Rongrong Zhai, San Shwe Hla, Ramesh Thiruvenkatachari, Keith Burnard (2019), *Towards Zero Emissions from Fossil Fuel Power Stations*, International Journal of Greenhouse Gas Control, Volume 87, 2019, Pages 188-202.
https://www.sciencedirect.com/science/article/pii/S1750583618308934

Patrick Brandl, Mai Bui, Jason P. Hallett, Niall Mac Dowell, *Beyond 90% capture: Possible, but at what cost?*,
International Journal of Greenhouse Gas Control, Volume 105, 2021, 103239,
https://doi.org/10.1016/j.ijggc.2020.103239 ; https://www.sciencedirect.com/science/article/pii/S1750583620306642

Shah, M.I., da Silva, E.F., Gjernes, E. and Åsen, K.I. (2021) , *CO_2 capture cost reduction study for CCGT flue gas, based on MEA at TCM*, GHGT15
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3821061
Pilot scale trials achieving 95-99% capture using ~35% w/w MEA from ~4% v/v CO_2 flue gas, 3.7-4.0 GJ/tCO_2.



UPCC Study Comment:
Mainly looked at <90% capture, 94% was limit of operation, due to assumed compressor characteristics.

Total Electricity Output Penalty of CO_2 capture and compression at different capture levels under variable and fixed stripper pressure operation – limit of 94% for plant designed for 90% capture level (Aspen Plus rate-based model – Aspen Tech 2012)
Errey, O.C. (2018) Variable capture levels of carbon dioxide from natural gas combined cycle power plant with integrated post-combustion capture in low carbon electricity markets, PhD thesis, University of Edinburgh. https://era.ed.ac.uk/handle/1842/33240

CO_2 Capture Facility at Kårstø, Norway

Front-End Engineering and Design (FEED) Study Report

Submittal to GASSNOVA

13 January 2009, Revision 1

Redacted for Distribution as per Gassnova Instructions 3 April 2019

25474-000-30R-G04G-00001

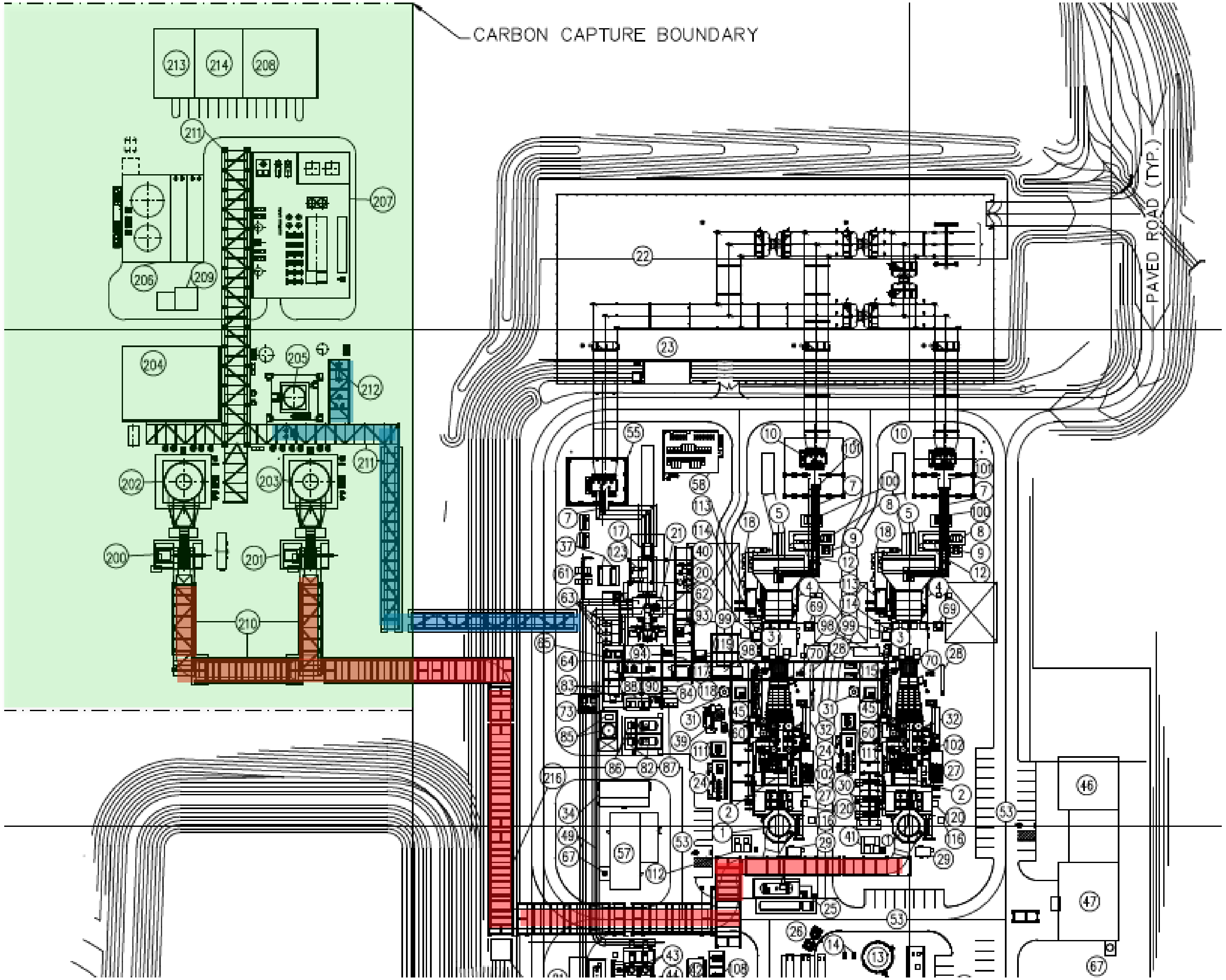
10112936-PB-G-DOC-0005

https://ukccsrc.ac.uk/open-access-carbon-capture-and-storage-at-karsto-norway/

320-CCC FEED Study

Integrated plot plan on Sherman site:

- Handles about 60% of maximum flue gas flow
- This ensures high PCC capital utilisation



GHGT15 paper, 'An open-access, detailed description of post-combustion CO_2 capture plant'
https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3814671

Sherman retrofit design features

Design shaped by operation in ERCOT and support from 45Q

- Solvent: 35 wt% MEA - previous study suggests competitive costs and open-access
- Design capture level: 85% of the CO_2 in the flue gas going to the absorber
- Design flue gas flow: 704 kg/s, around minimum stable generation flow, into two absorbers
- CO_2 captured: 129 t/h of CO_2
- Heat for regeneration: 3.65 GJ/tCO_2 total
- Heat recovery: 0.14 GJ/tCO_2 from CO_2 compressors intercooling, used for semi-lean flash
- Lean loading: 0.254 mole CO_2/mole MEA from stripper
- Rich loading: 0.475 mole CO_2/mole MEA
- Liquid/gas ratio: 1.07 mass ratio
- CO_2 delivery pressure: 151 bara, centrifugal compressor, send out pump and dehydration

Estimated variation in additional electricity cost for retrofit to a natural gas combined cycle power plant

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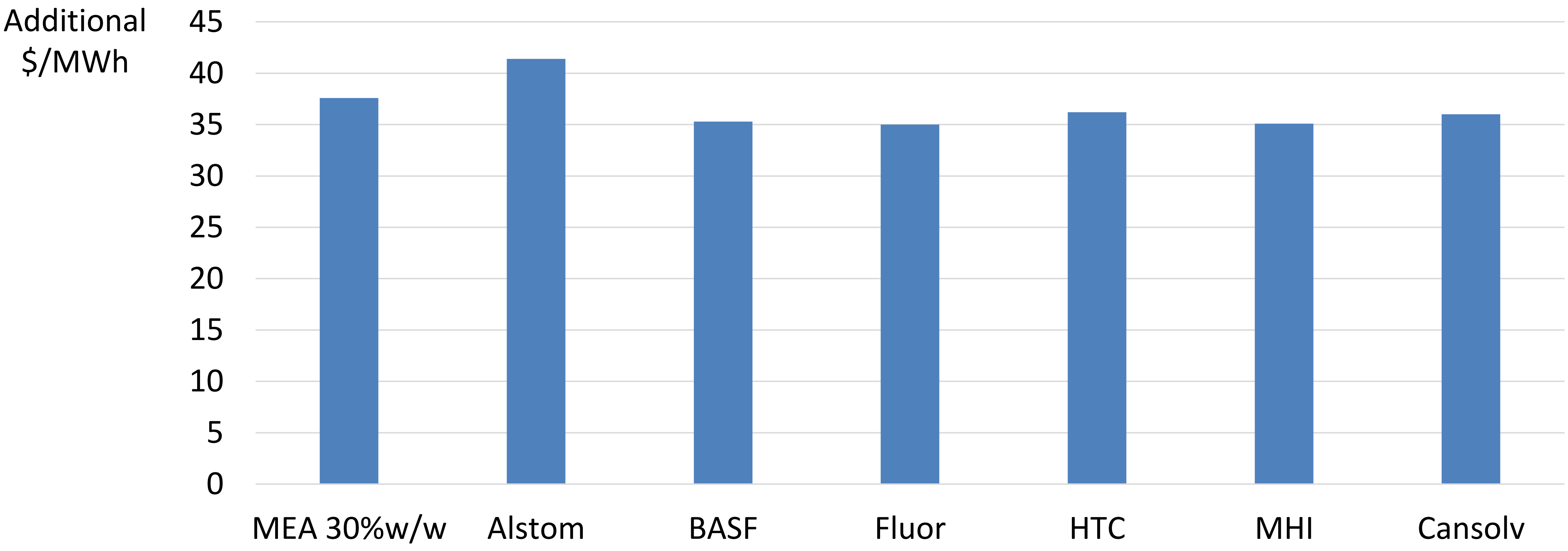
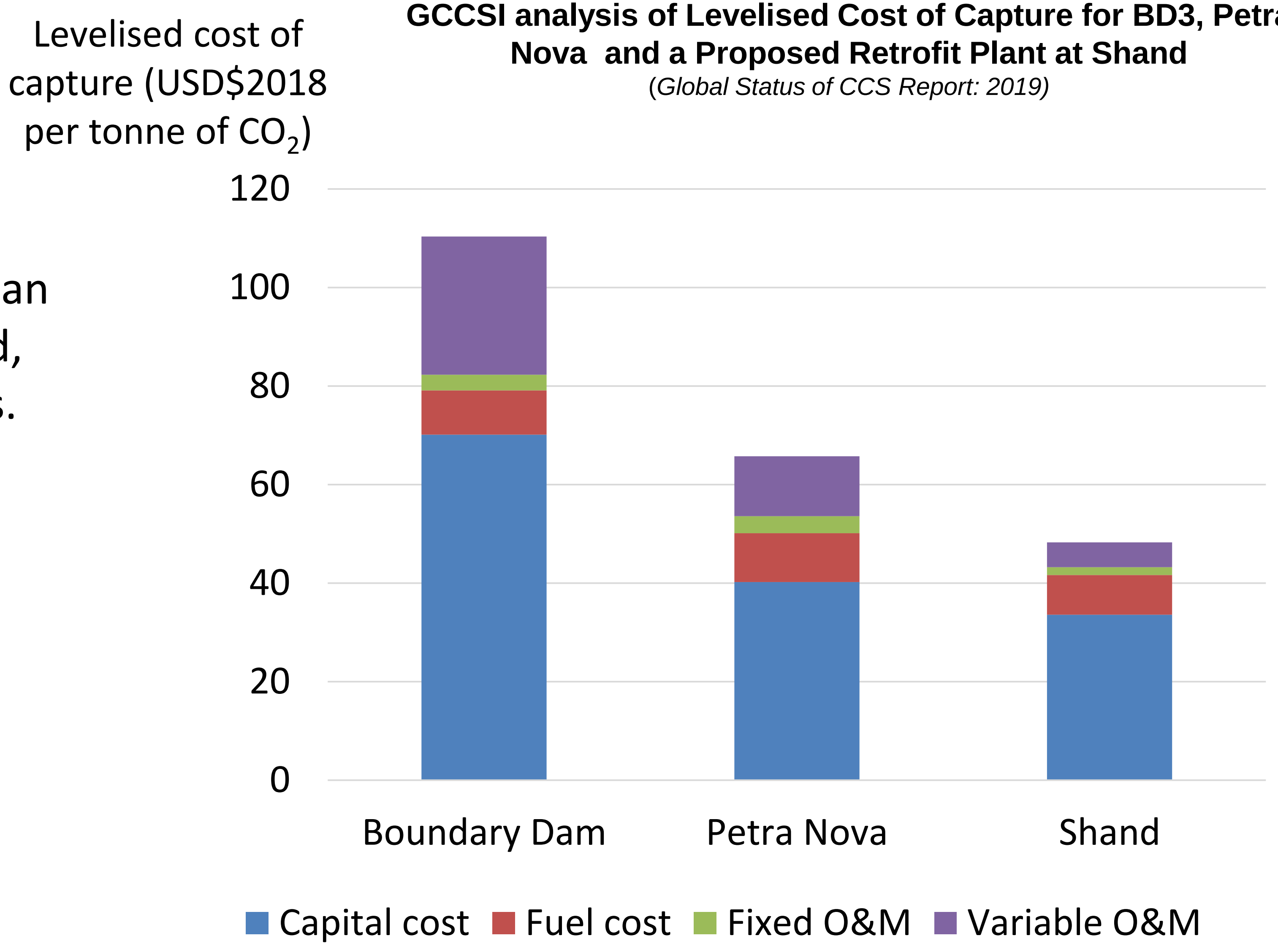


Nexant (2016), *World Bank Pre-Feasibility Study for Establishing a Carbon Capture Pilot Plant in Mexico - Full-Scale Poza Rica NGCC PCC Retrofit Incremental Electricity Cost ($/MWh) for 85% CO2 Capture*, https://www.gob.mx/sener/en/documentos/pre-feasibility-study-for-establishing-a-carbon-capture-pilot-plant-in-mexico?idiom=en , download https://www.gob.mx/cms/uploads/attachment/file/107318/CCPP_Final_Report.pdf

Solvent costs with ‘dirty’ flue gases

- Solvent management costs can also be higher than expected, and overwhelm energy costs.

GCCSI analysis of Levelised Cost of Capture for BD3, Petra Nova and a Proposed Retrofit Plant at Shand
(Global Status of CCS Report: 2019)



Sherman retrofit solvent management

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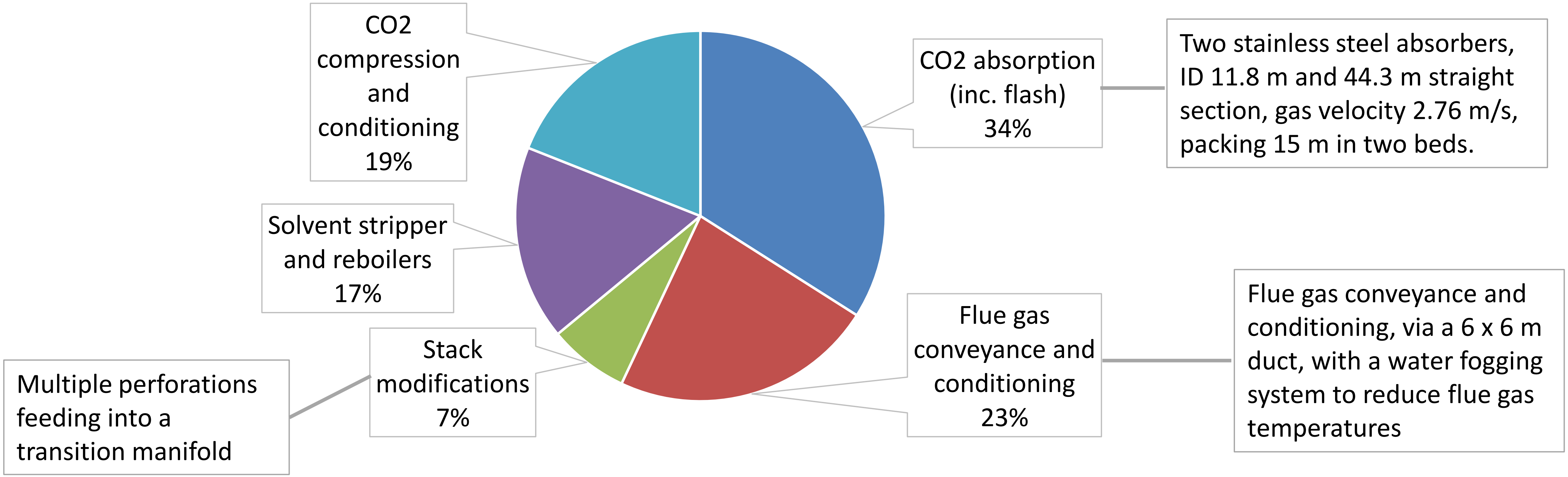
Design shaped by operation in ERCOT and support from 45Q

- Semi-continuous thermal reclaimer
- Processes inventory every 28 days
- Two stages with 150^{o}C operating temperature in both
- First stage vents to the stripper at 2.6 bara, for heat recovery.
- Second stage vents to the top of the absorber, at near atmospheric pressure.
- Solvent recovery estimated ≥90%
- Net solvent consumption 2 kg MEA/tCO_2
- MEA supply cost $1.15/kg delivered, 99% purity, iron and chlorine free.
- Reclaimer bottoms disposal costs estimated at $500/t

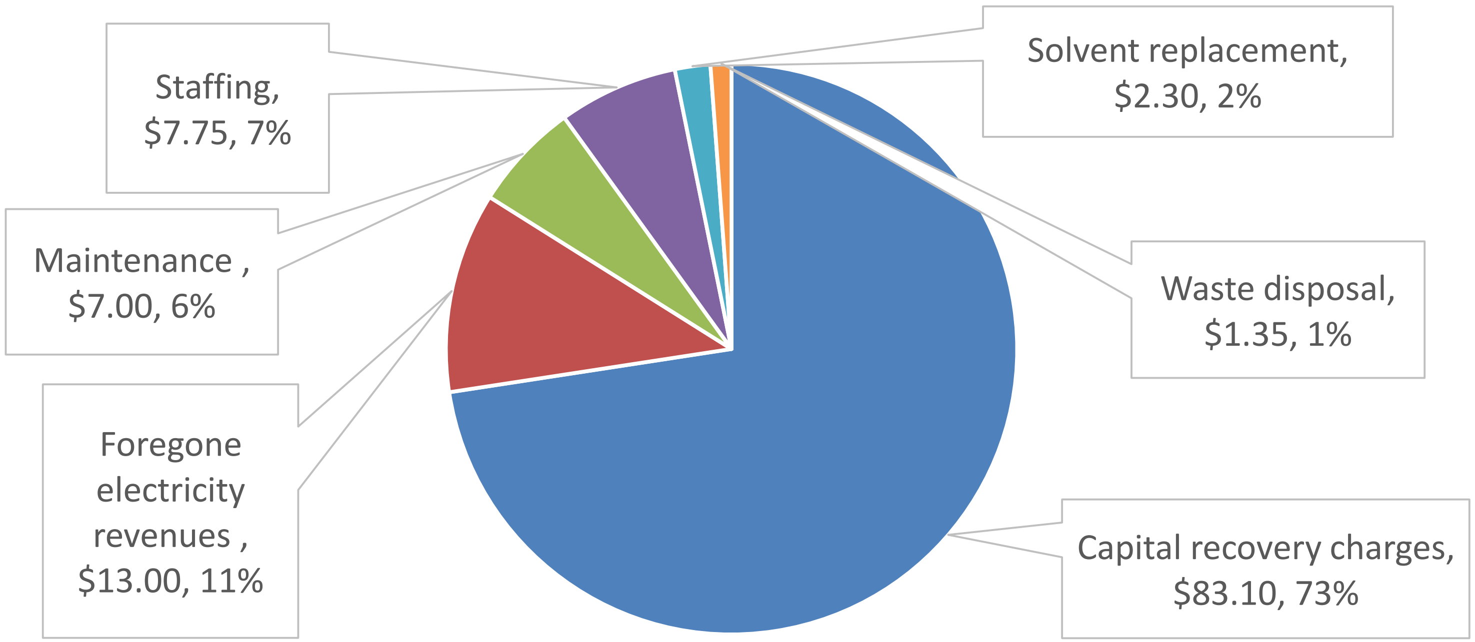
Sherman retrofit capital costs

- Overall capital cost estimate $477M, including indirect costs, owner's and contractor's costs and interest during construction
- Completion 30 months from notice to proceed



Sherman retrofit capture costs

- Estimated baseline CO_2 capture costs \$114.50/tCO_2
- PCC operation for an average of 5000 hours per year
- Dominated by capital recovery charges
  - 70/30 debt to equity ratio, 6% interest rate on debt over 15 years, 12% return on equity
- Net output is reduced by 67.3 MW when supplying PCC steam and electricity requirements
  - Not operated when electricity prices high (up to \$9000/MWh) or when power plant not operating,
  - Average foregone electricity revenue \$25/MWh



Sherman FEED concluding remarks

- Detailed open-access FEED design + 200 documents, look out for DE-FE0031848
- Simulation models useful but not precise enough for better than +/- 15% commercial sizing
- And no way of assessing solvent management costs and emissions without long-term tests that include reclaiming – <u>rate of removal for impurities must match addition + formation</u>
- Need pilot test rig ~1 m absorber column, running 12-18 months on real flue gas, capital cost ~$20M
- Realistic testing required to get precise commercial design parameters for detailed plant design
- Also to explore trade-off between CAPEX and OPEX that reflects reality of current and future markets in all sectors
- <u>Hard evidence is the only guarantee that is worth having!</u>

UPCC/Co-Cap results

- TERC modelling based on process design for DOE FEED study that has 85% design capture level
- Modelling using US DOE CCSI software, which has been calibrated against NCCC (US) and TCM (Norway)
- NCCC web site - https://www.nationalcarboncapturecenter.com
- TCM web site - https://tcmda.com/
- $CCSI^2$ web site - https://www.acceleratecarboncapture.org/

CCSI-Toolset MEA Steady State Model used to explore options

https://github.com/CCSI-Toolset/MEA_ssm

- Initial difficulty in matching absorber height between different models
- But can adjust L/G, not just packing height
- Trade-off between capital and energy costs – not fully explored
- Can also adjust lean loading – see next slide

Packing Height, m	Lean Loading, mol/mol	CO_2 Capture Rate, %	Rich Loading, mol/mol	L/G kg/kg	L/G for 85%	Rich loading mol/mol
ProMax® Base Case: 5 stages/15 m	0.254	85.0	0.475	1.069	-	-
CCSI/Aspen:						
10	0.254	66.4	0.4267	1.068	2.1	0.3713
15	0.254	75.1	0.4457	1.066	1.367	0.4226
20	0.254	79.9	0.4561	1.066	1.175	0.4501
25	0.254	82.6	0.4621	1.065	1.106	0.4605
30	0.254	84.2	0.4656	1.065	1.077	0.4653
40	0.254	85.6	0.4688	1.064	1.056	0.4689
34.28	0.254	85.0	0.4674	1.065	-	-

Semi-lean assumed to be injected 40% down the packing in all cases

CCSI-Toolset MEA Steady State Model

Different packing heights, L/G and lean loading varied together to give 85% capture

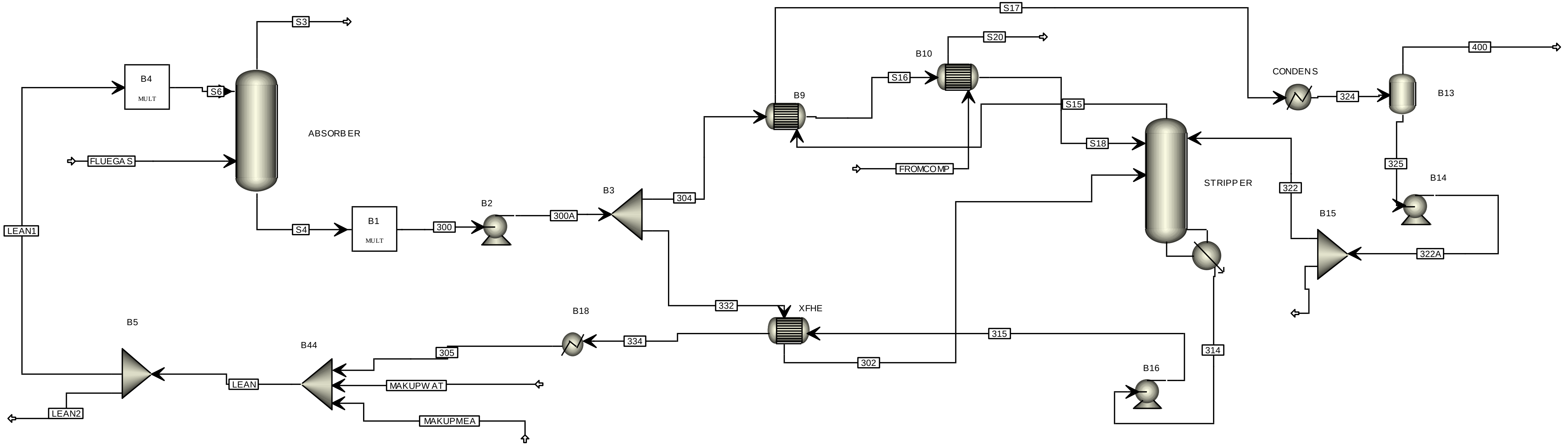
- 85% capture can be achieved at a wide range of L/G ratios and lean loading, but stripper energy minimised at a particular L/G + lean
- Pronounced minimum in energy at a specific pair of values if the amount of packing does not give ~0.45 rich loading, also higher energy requirement, e.g. with 10 m packing
- Energy relatively insensitive to L/G + lean value above minimum value for cases with more packing relative to the capture level required (not shown here, but confirmed by UPCC/Co-Cap data)

Case	Rich Loading, mol/mol	Reboiler Duty, MW	Stripper Bottom Temp, °C	Lean Loading, mol/mol	L/G kg/kg
ProMax® results	0.475	125.45	131	0.254	1.069
34.28 m packing	0.467	116.97	126.92	0.254	1.065
15 m, design L/G	0.436	132.43	128.57	0.216	1.069
15 m, min energy L/G	0.449	127.74	131.10	0.12	0.720
10 m, higher L/G	0.398	153.55	130.46	0.15	0.992
10 m, min energy L/G	0.401	151.06	130.87	0.13	0.905

UPCC/Co-Cap Aspen PFD

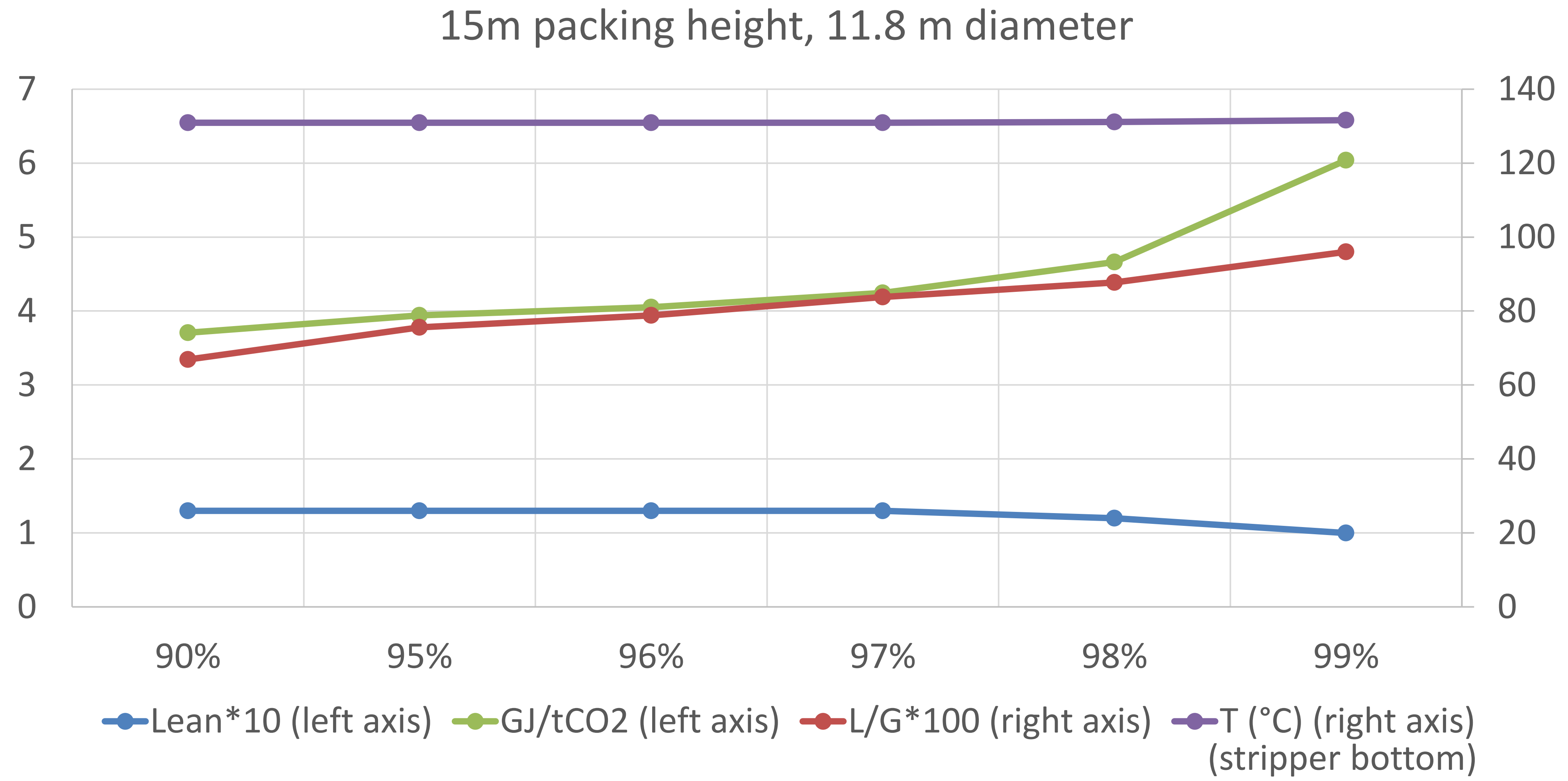
- Two identical absorbers
- Absorber height, 15-24 m (each)
- 11.8 m diameter unless shown otherwise
- Stripper height, 20m
- MellapakPlus™ 250Y
- Rich split, 5%
- Heat from compressors and stripper top is utilised to heat split and reduce reboiler heat input

- 35% w/w MEA
- Capture rates, 90% - 99%
- Lean, ~ 0.1 - 0.25 mol/mol
- L/G, ~ 0.6 - 1.1



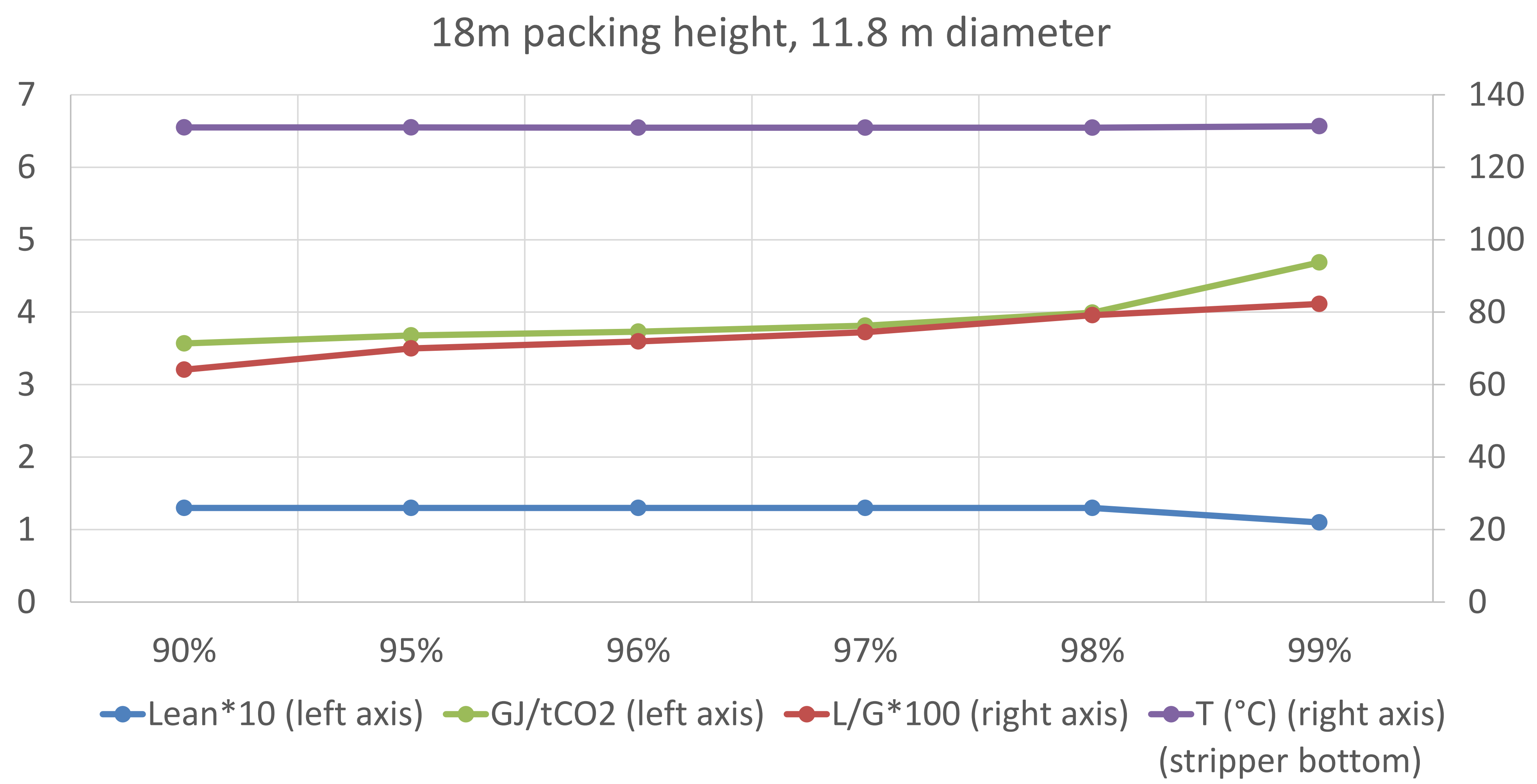
UPCC/Co-Cap results – 15 m absorber

L/G and lean loading varied together to give 90, 95-99% capture with minimum reboiler heat input



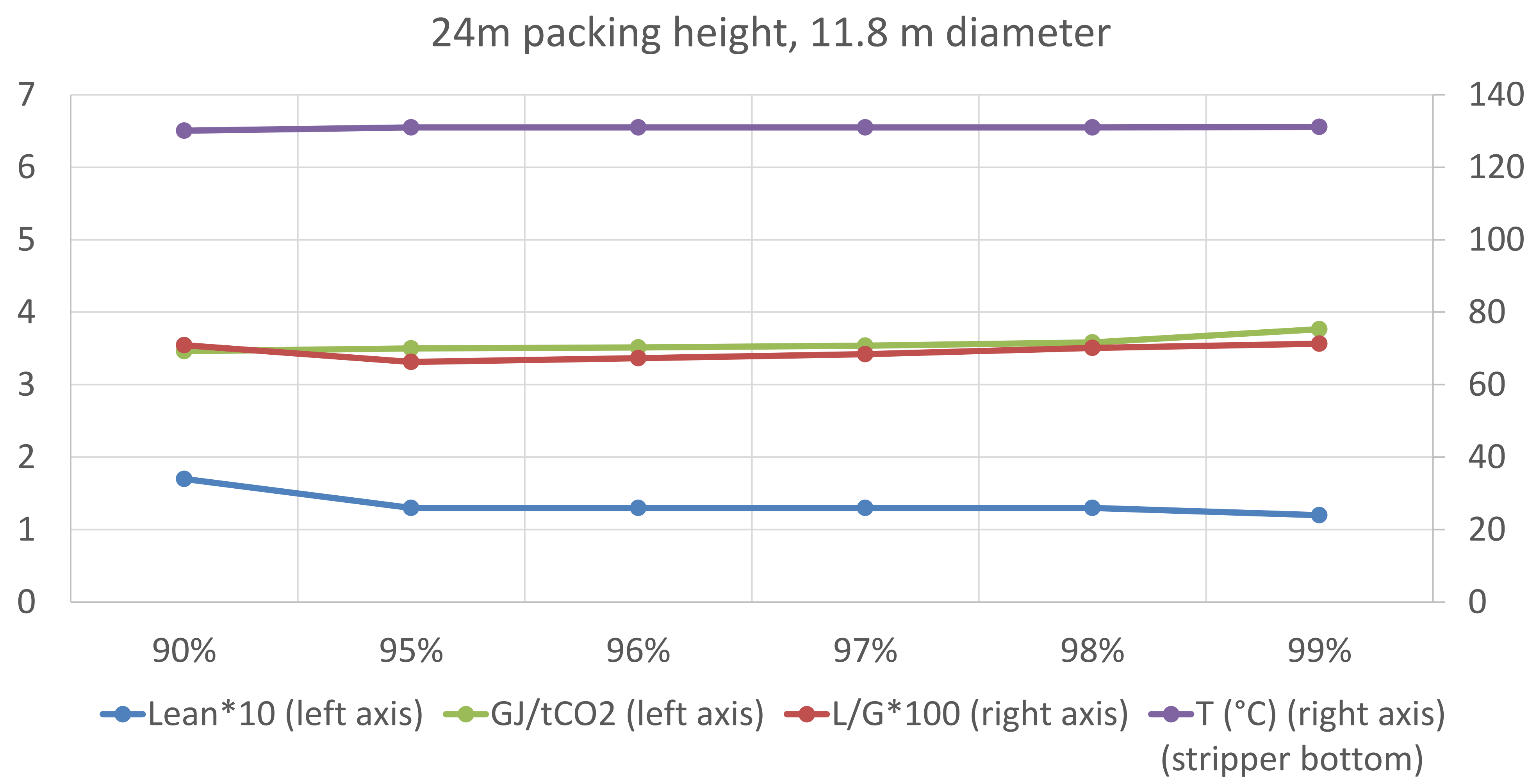
UPCC/Co-Cap results – 18 m absorber

L/G and lean loading varied together to give 90, 95-99% capture, with minimum reboiler heat input



UPCC/Co-Cap results – 24 m absorber

L/G and lean loading varied together to give 90, 95-99% capture, with minimum reboiler heat input



UPCC/Co-Cap results – 18 m absorber

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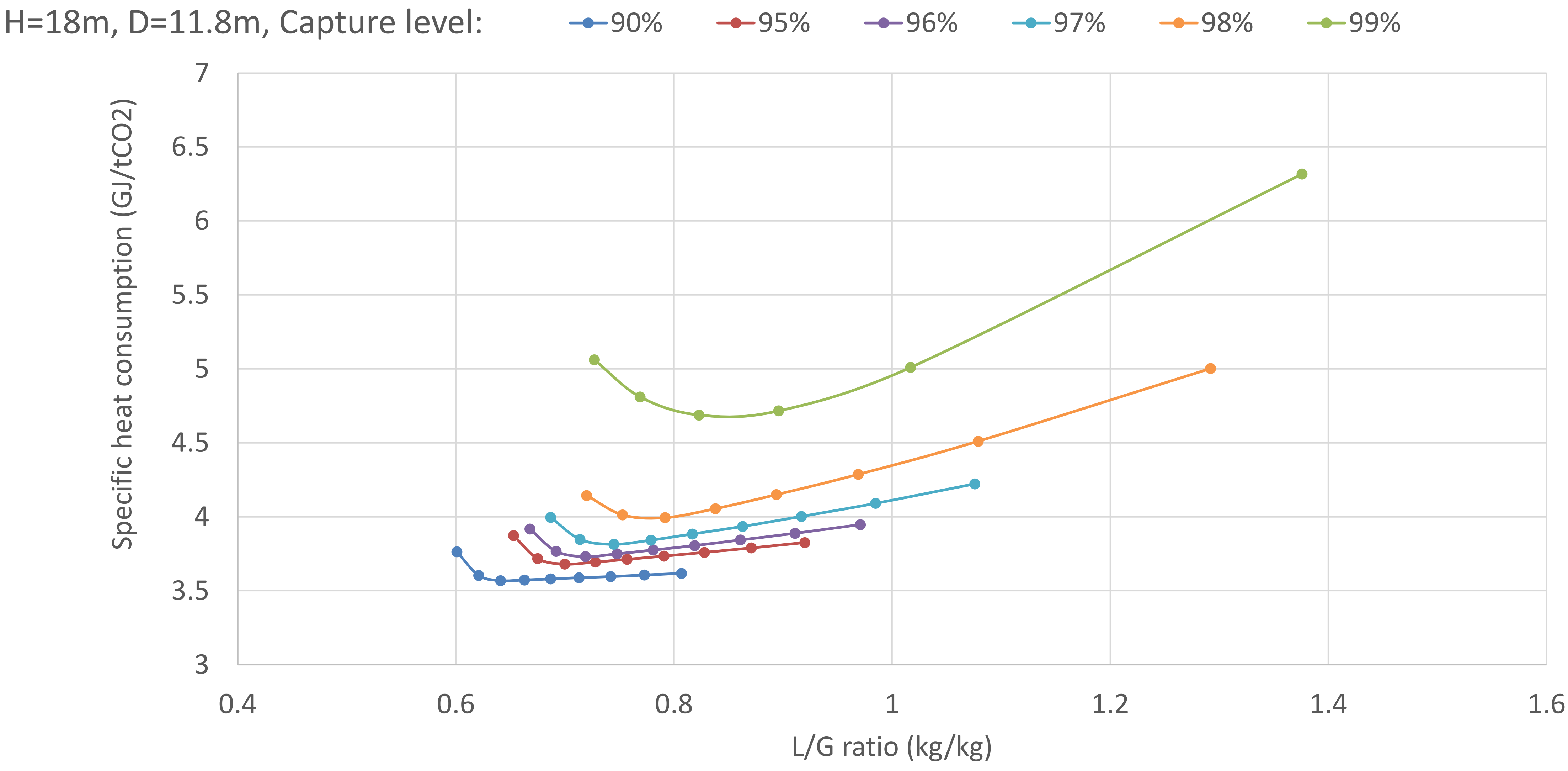
L/G and lean loading varied together to give 90, 95-99% capture, with varying consequences for stripping heat requirement



UPCC/Co-Cap configuration, 18 m, 95% capture

Effect of reduced gas and liquid inlet temperatures

Temperatures	ºC	Gas=50, L=50	Gas=40, L=50	Gas=40, L=40	Gas=30, L=50	Gas=30, L=40
Flue gas flow rate (wet)	kg/s	721.07	700.28	700.28	686.93	686.93
CO_2 in	kg/s	42.09	42.09	42.09	42.09	42.09
Absorber packing height	m	18	18	18	18	18
Absorber diameter	m	11.8	11.8	11.8	11.8	11.8
CO_2 capture level	%	95	95	95	95	95
Lean loading to absorber	molCO_2/molMEA	0.19	0.19	0.19	0.19	0.19
Rich loading out of absorber	molCO_2/molMEA	0.4299	0.4327	0.4316	0.4267	0.4255
L/G ratio	kg/kg	0.920	0.935	0.939	0.977	0.982
T, bottom stripper	°C	129.47	129.56	129.45	129.65	129.54
Reboiler heat input	MW	152.99	151.11	152.08	153.54	154.48
Specific heat consumption	GJ/tCO_2	3.83	3.78	3.80	3.84	3.86

Effect of increasing absorber diameter for 18 m packing

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Appears that extra packing volume is about half as effective used in increasing cross sectional area as in increasing height (e.g. compare with 24m packing results)

Flue gas flow rate	kg/s	721.07	721.07	721.07	721.07	721.07
CO_2 in	kg/s	42.09	42.09	42.09	42.09	42.09
Absorber packing height	m	18	18	18	18	18
Absorber diameter	m	11.8	13.2	14.45	15.61	16.7
Extra cross sectional area			25%	50%	75%	100%
Flue gas inlet temperature	ºC	51	51	51	51	51
CO_2 capture level	%	95	95	95	95	95
CO_2 concentration	%	3.72	3.72	3.72	3.72	3.72
Lean loading to absorber	$molCO_2/molMEA$	0.13	0.13	0.13	0.13	0.13
Rich loading out of absorber	$molCO_2/molMEA$	0.446	0.4568	0.4624	0.4655	0.4673
L/G ratio	-	0.7	0.676	0.665	0.659	0.655
T, bottom stripper	ºC	130.95	130.97	130.96	130.94	130.94
Reboiler heat input	MW	147.16	142.58	141.06	140.83	140.13
Specific heat consumption	GJ/tCO_2	3.68	3.57	3.53	3.52	3.50

UPCC/Co-Cap results summary

- High capture levels <u>modelled</u> as being achievable in a similar plant configuration to the Sherman FEED study
- Lean loading determines maximum capture level
- Inlet flue gas CO_2 determines maximum rich loading
- Stripper specific heat input is a function of liquid flow (lower better) and rich loading (higher better) as well as lean loading (higher better)
- If L/G is too high for a given lean loading then the rich loading cannot reach the maximum value, however much packing is used
- For Sherman flue gas flow and absorber diameter 15 m is too short for 99% capture, 18 m requires significantly-increased energy (but less for 98% and below) and 24 m is probably adequate (for current CCSI model kinetics)
- Absorber diameter can also be increased, with less effective use of packing but may save adding an extra bed
- Results are in the same area as TCM 35% MEA tests

AECOM (2020) for BEIS, *Start-up and Shut-down times of Power CCUS Facilities*. https://www.gov.uk/government/publications/start-up-and-shut-down-times-of-power-carbon-capture-usage-and-storage-ccus-facilities

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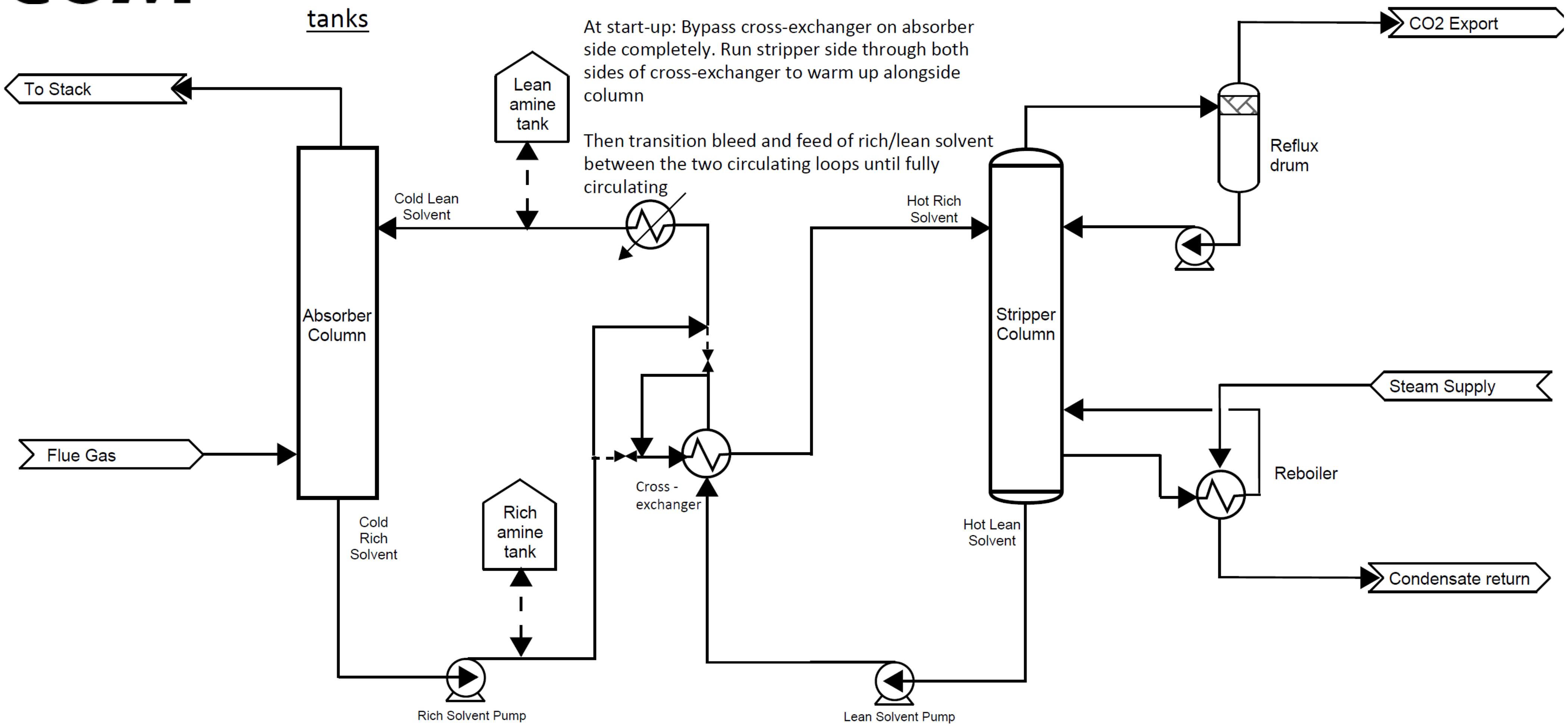
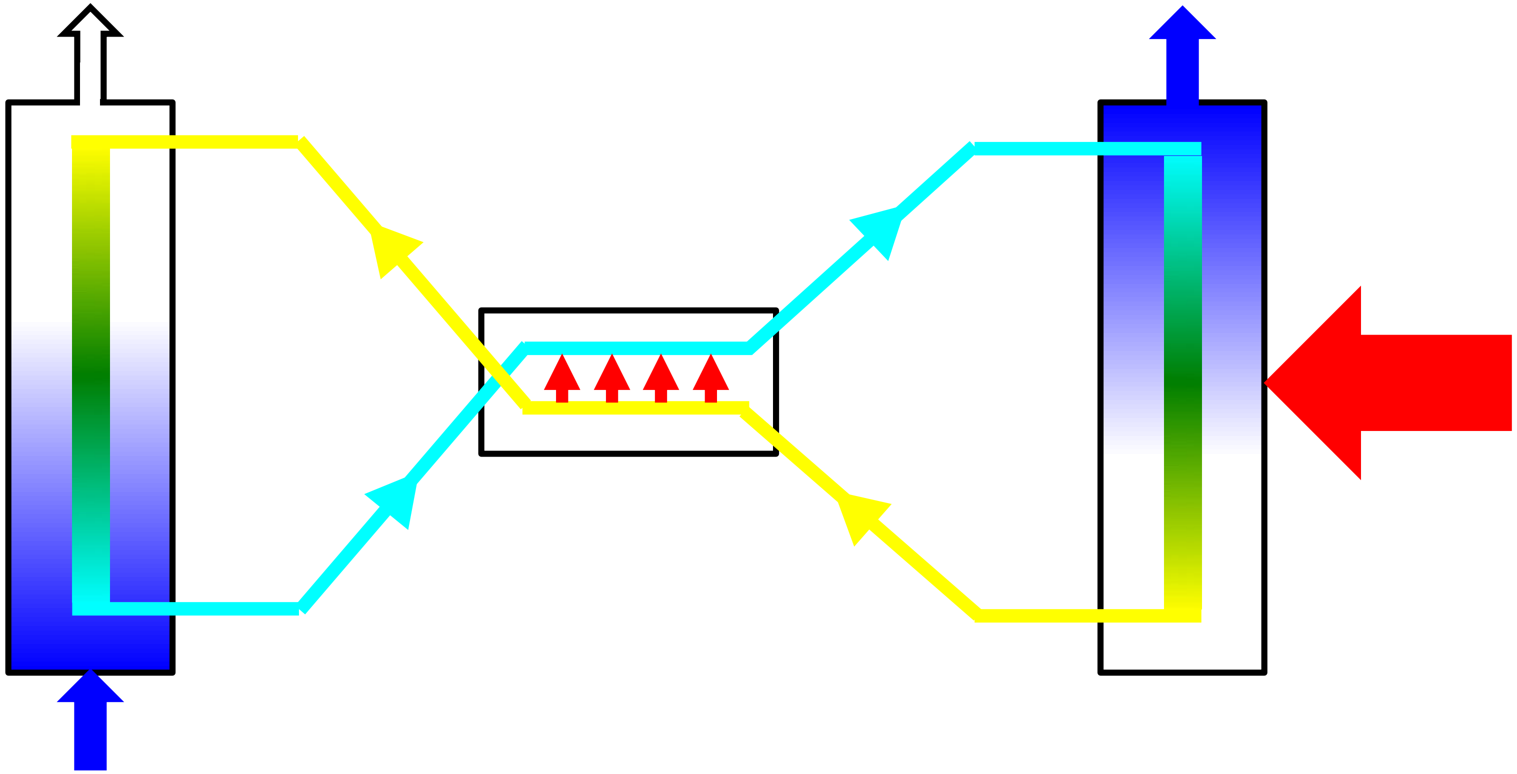
Simplified process flow diagram of base case at start-up - hybrid of segregated inventory start with two storage tanks



Issue being addressed is GT starting up and running for extended periods (especially on warm or cold starts) before steam is available to regenerate PCC solvent.

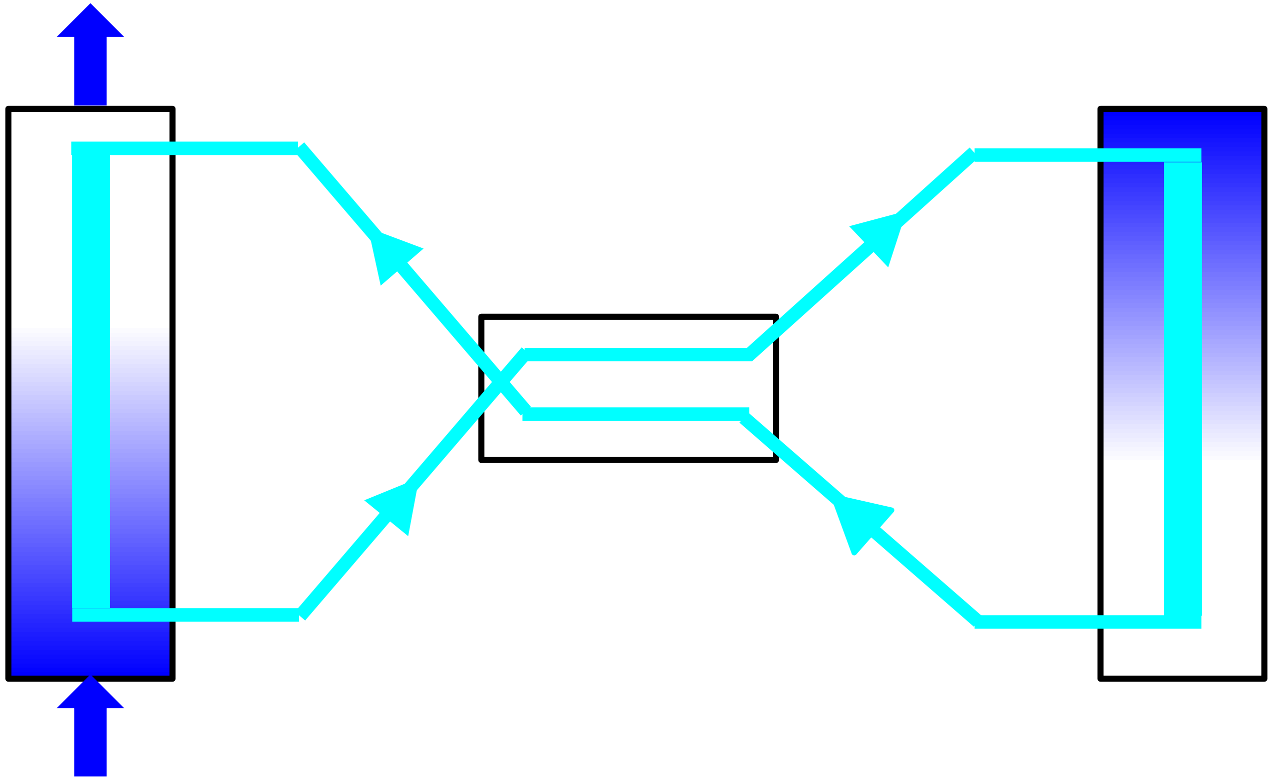
PCC without storage: Normal operation



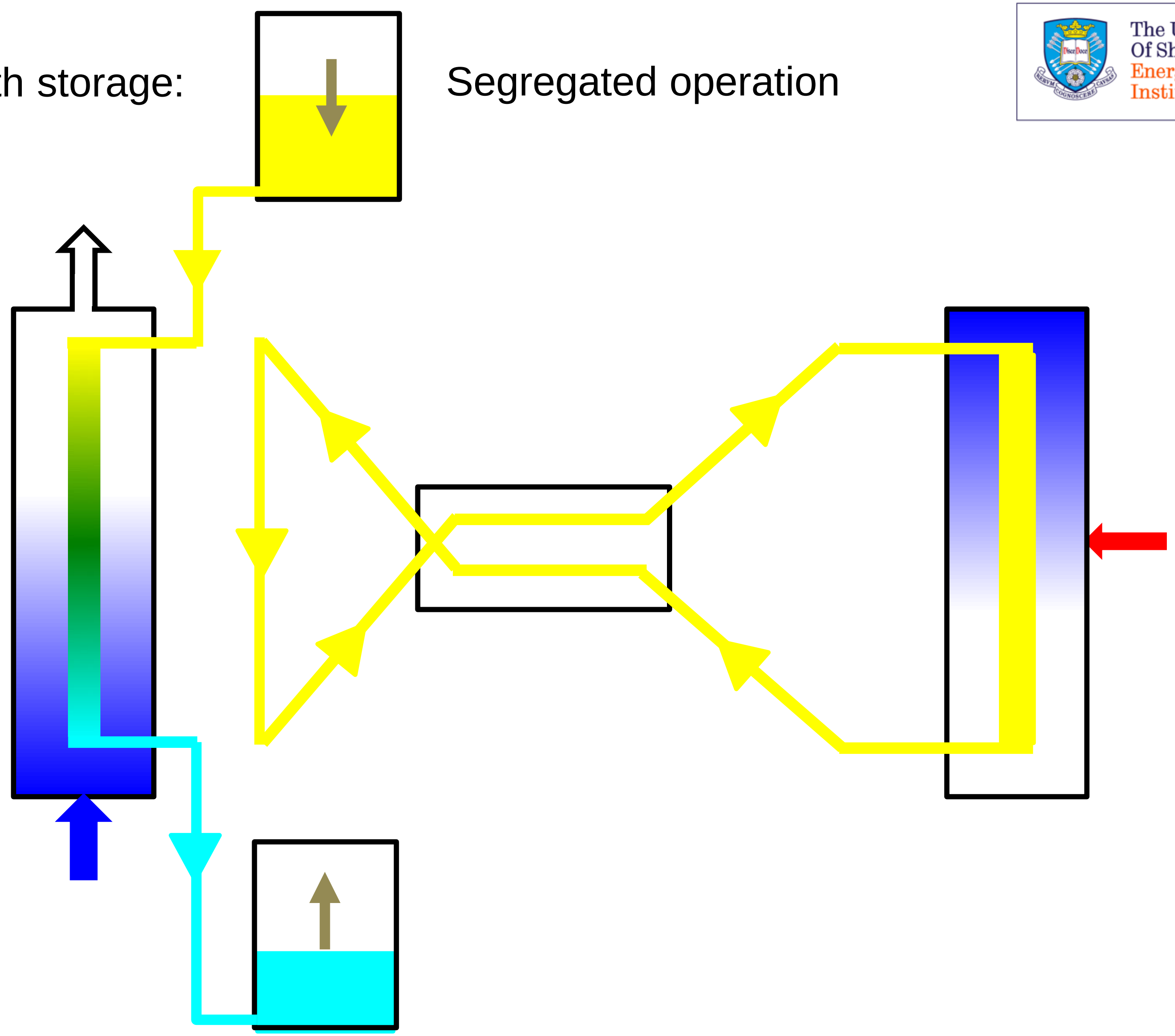
PCC without storage:

No heat available

Solvent inventory will have absorbed some CO_2, but capacity limited



PCC with storage: Segregated operation



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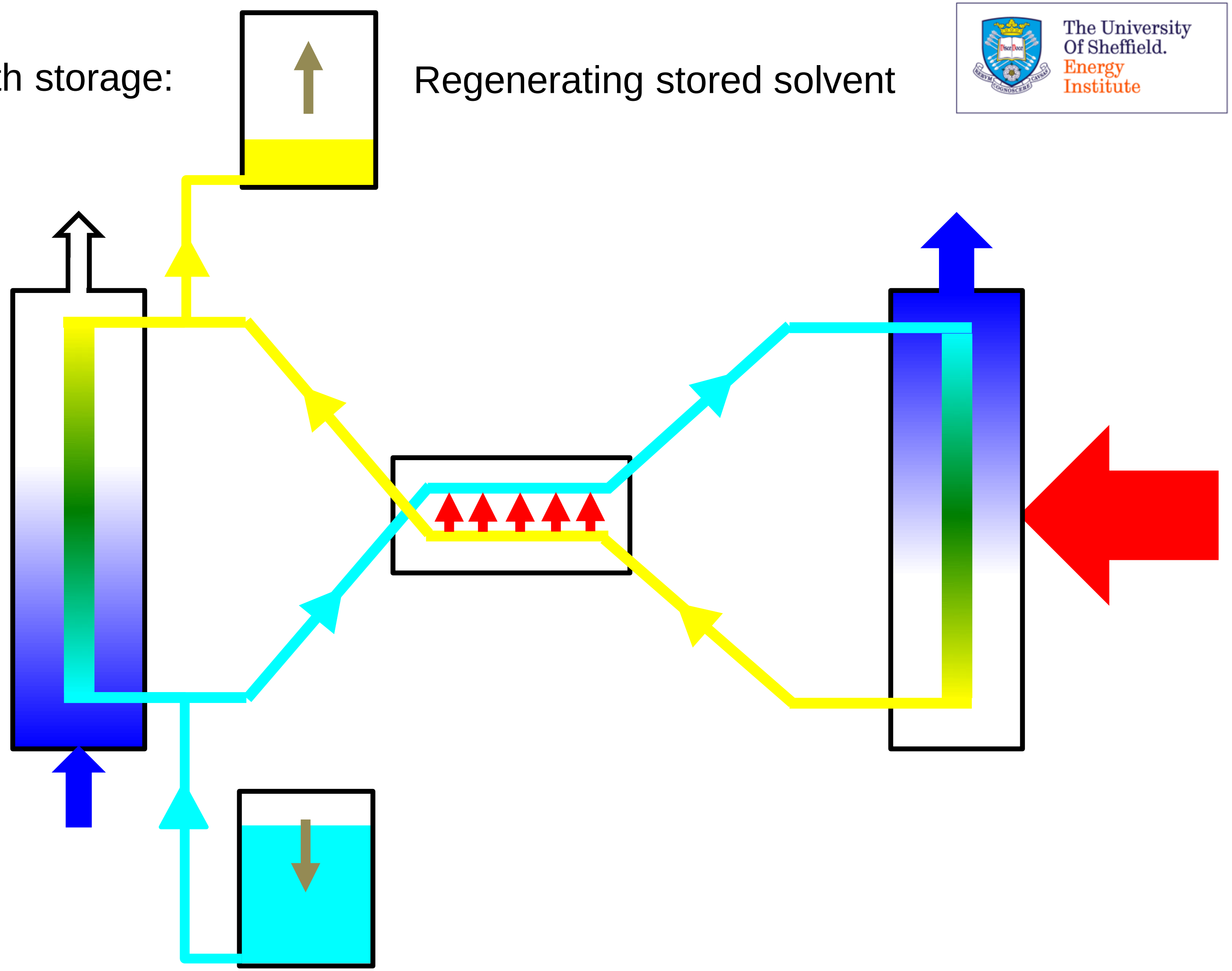
PCC with storage: Regenerating stored solvent



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PCC with storage: Normal operation

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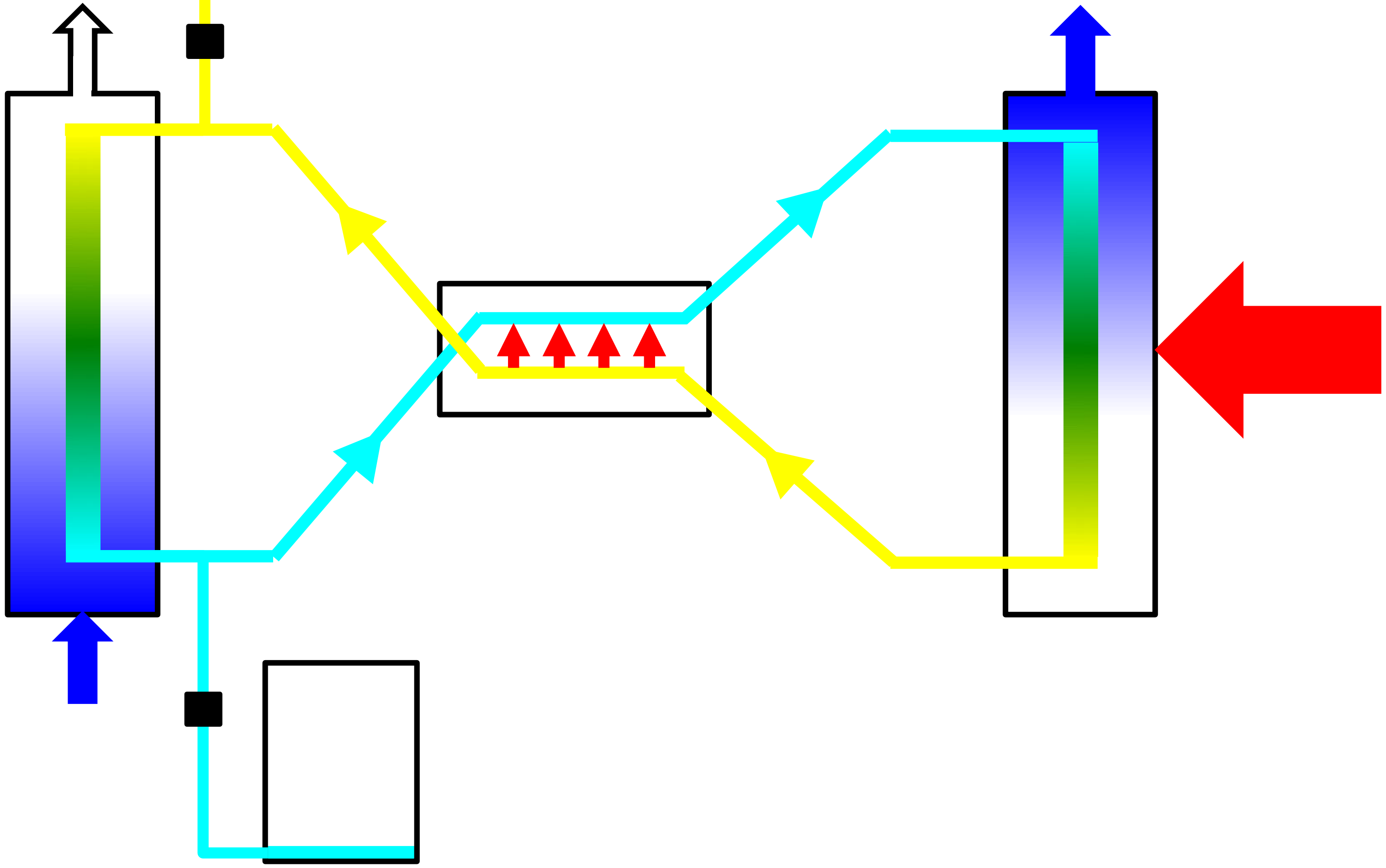

Example of absorber operation using stored solvent at reduced flow during reduced GT load

- Stored solvent can be used at lower flow rates during periods when GT is held at lower output while the steam cycle warms up

		Normal operation	IGV maintains CO_2 conc'n	IGV maintains CO_2 conc'n- optimised flow	No IGV	No IGV – optimised flow
Flue gas flow rate	%	100	60	60	100	100
CO_2 in	%	100	60	**60**	60	**60**
CO_2 concentration	% v/v	3.725	3.725	3.725	2.202	2.202
Liquid flow rate	%	100	60	**52.2**	100	**74.8**
Lean loading to absorber	$molCO_2/molMEA$	0.203	0.203	0.203	0.203	0.203
Rich loading out of absorber	$molCO_2/molMEA$	0.424	0.43	0.457	0.337	0.388
CO_2 capture level	%	95	97.5	95	96.8	95

18m absorber, 11.8 m diameter, 95% capture with assumed design L/G ratio of 1

Final thoughts on operation at 95%+ capture rates

- MHI study and other studies using MEA give similar trends of nearly pro-rata costs per tonne of CO_2 captured up to ~99% or higher on coal
- Supported by recently-published pilot tests at TCM
- But lack of comprehensive data in the modelling studies and tests; not clear that results are optimised (some are obviously not) and close checking impossible
- UPCC/Co-Cap comprehensive data now available
- The PCC plant has to be designed for a higher capture rate than e.g. 90% to achieve 95-99%; flue gas flows remain the same but other parameters will change, although perhaps the design can be generally similar to a ‘standard’ design:
    - Possibly, absorber packing height increase; will get lower energy but increase capital cost
    - Absorber diameter trends less clear
    - Possibly stripper diameter increase needed for higher steam and CO_2 flow rates
    - Solvent flow rate and XFHE duty – proportional to CO_2 captured or less – lower L/G likely
    - Steam to reboiler – more than proportional to CO_2 captured, increase depends on packing height and capture level
    - Compressor throughput – proportional to CO_2 captured

Some questions/issues for deployment

- Actual kinetics, VLE etc., for fresh MEA as well as for used solvent – CCSI has been calibrated over a fairly wide range of performance but not (much, or at all) on low CO_2 and also low L/G
- Absorber packing operation at lower L/G – packing and/or flow distributor issues
- Stripper design – CCSI uses equilibrium model
- Solvent degradation rates – stripper bottom temperatures are fairly high – may need to vary stripper pressures as well as reclaim more intensively
- Optimum solvent concentration – why should it be a round number?
- Commercial plant design parameters dependent on trade-off between capital and operating costs/revenues; will vary with market conditions and incentive mechanisms
- Detailed testing needed, at appropriate scale (>1 m diameter column) and duration (~ 1 year) and with full solvent management

UPCC/Co-Cap configuration absorber profile examples

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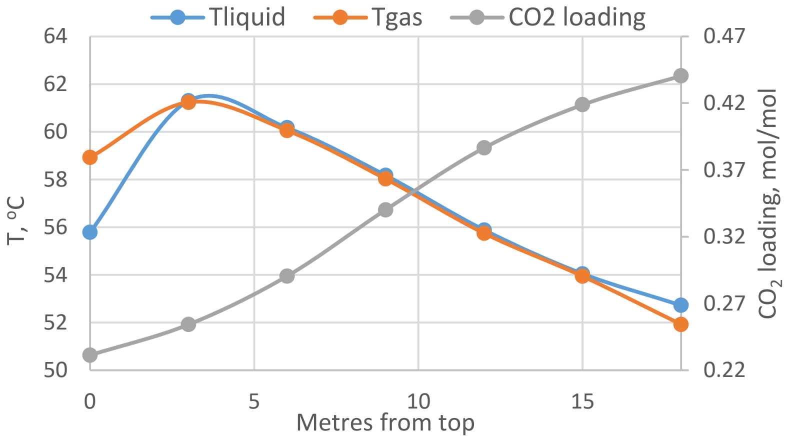
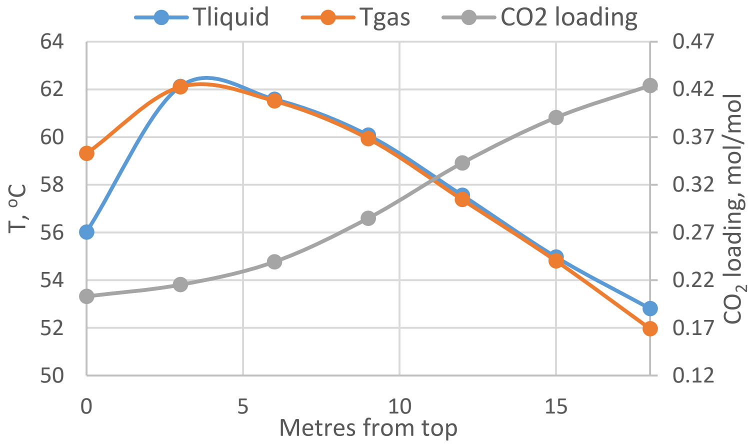
L/G=1, H=18m

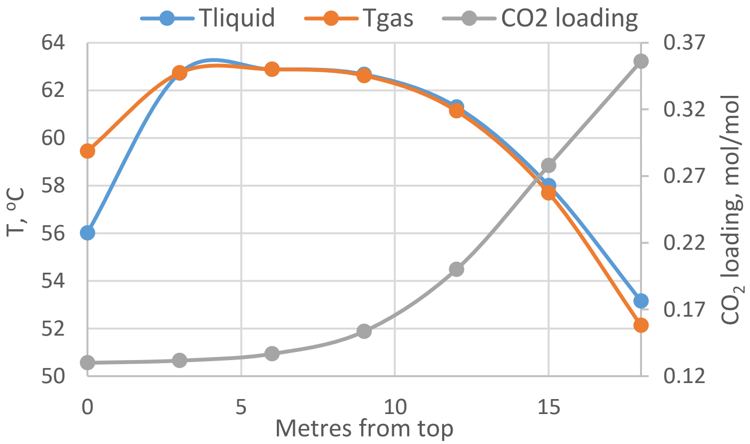
90%



95%

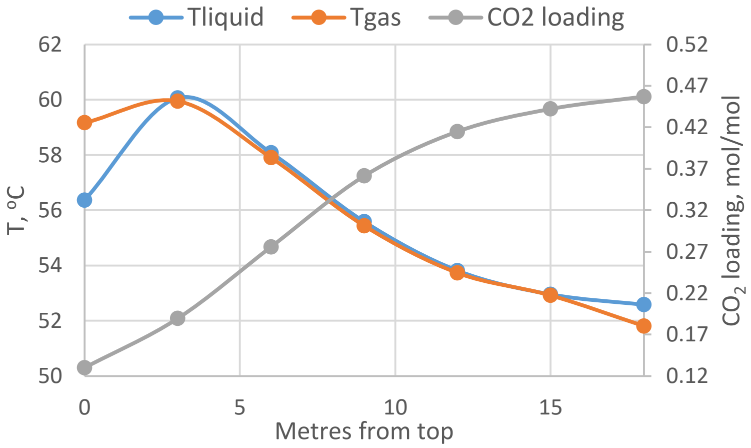


99%

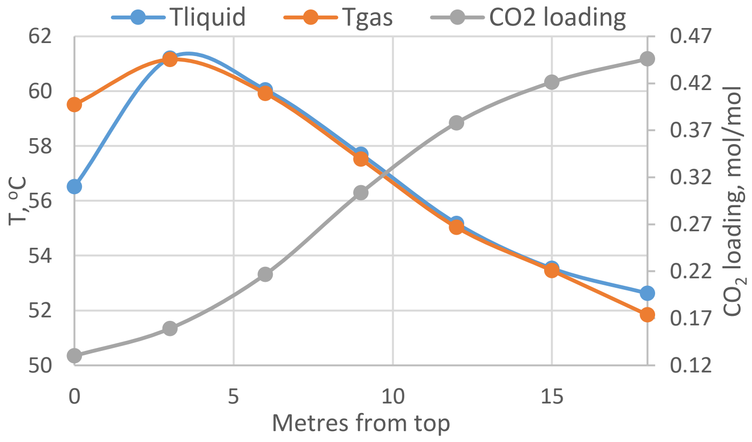


Optimum L/G, H=18m

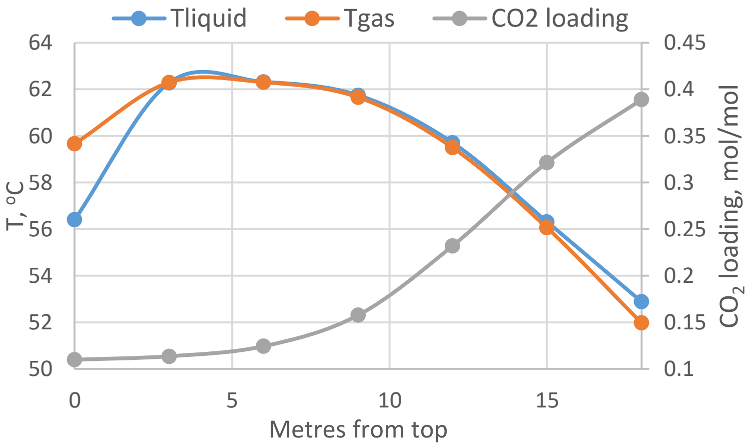
90%, L/G=0.64



95%, L/G=0.7



99%, L/G=0.82



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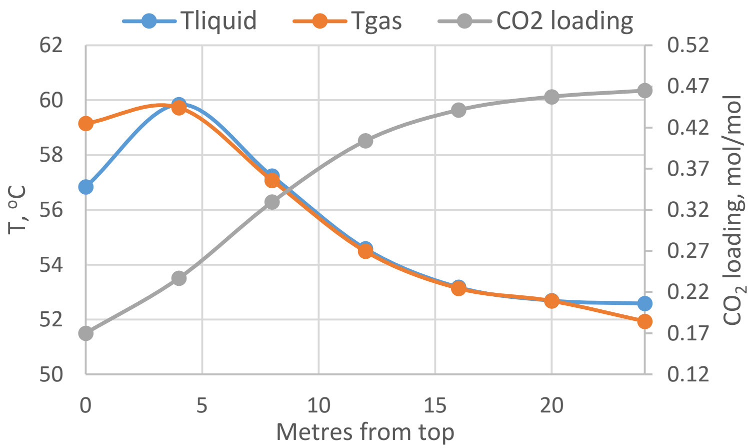
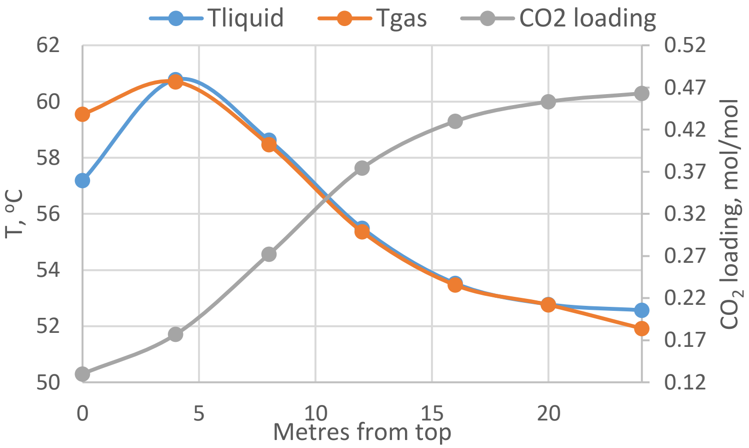
Optimum L/G, H=24m

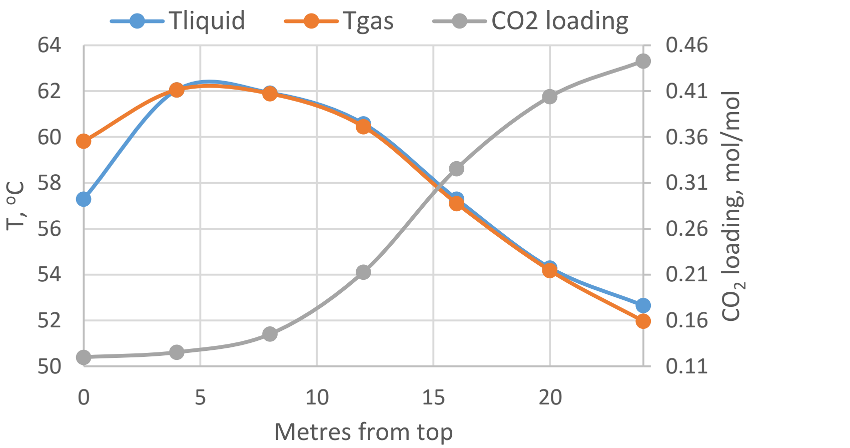
90%, L/G=0.71



95%, L/G=0.66

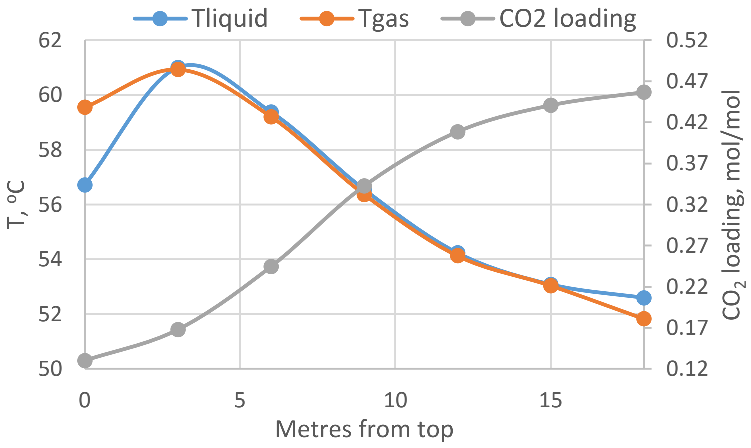


99%, L/G=0.71



Diff diameter, H=18m, 95%

D=13.2m, L/G=0.68



D=14.45m, L/G=0.67