Demonstrating flexible operation of the TCM CO_2 capture plant

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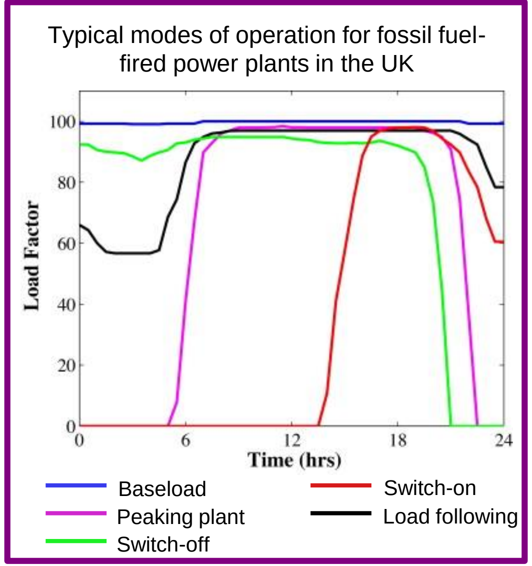
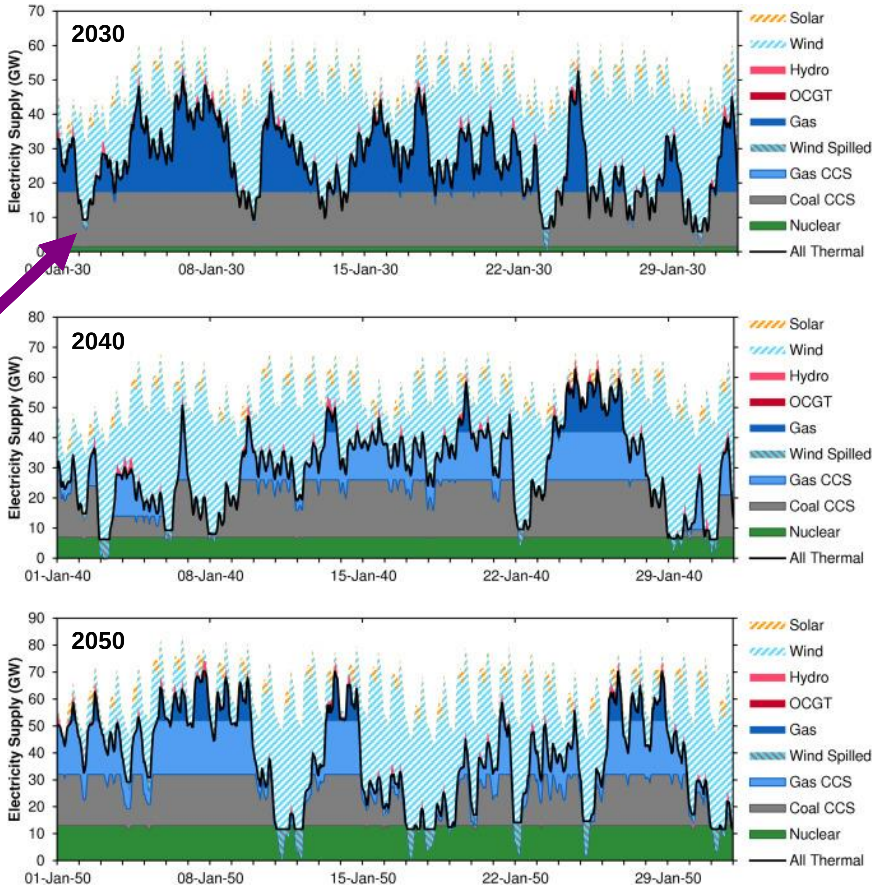
Flexible CCS in future electricity systems

To accommodate intermittent renewables, fossil fuel power plants will need to operate flexibly.

Coordinate the balance between electricity demand and CO_2 capture requirements.


Typical modes of operation for fossil fuel-fired power plants in the UK



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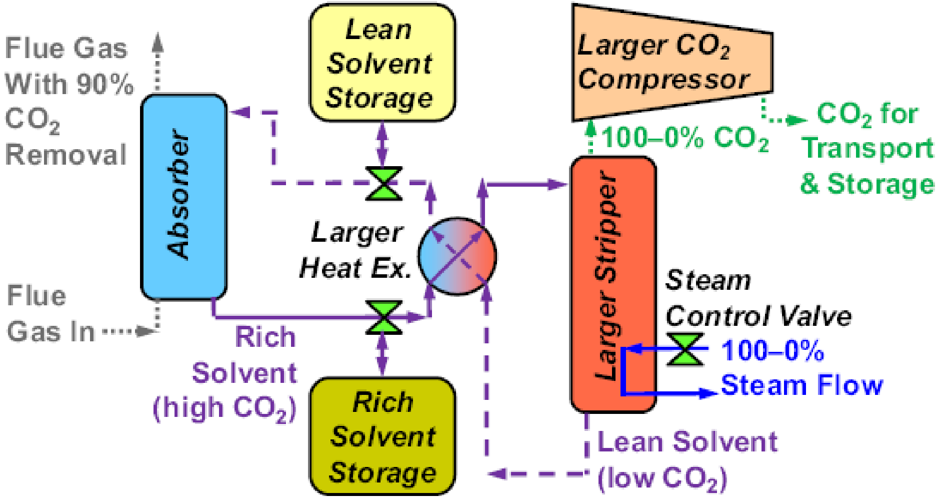
Mac Dowell, N. & Shah, N. (2015). Computers & Chemical Engineering, 74, 169–183.

Flexible Operation Strategies

Strategies that improve flexibility:

- Solvent storage tanks



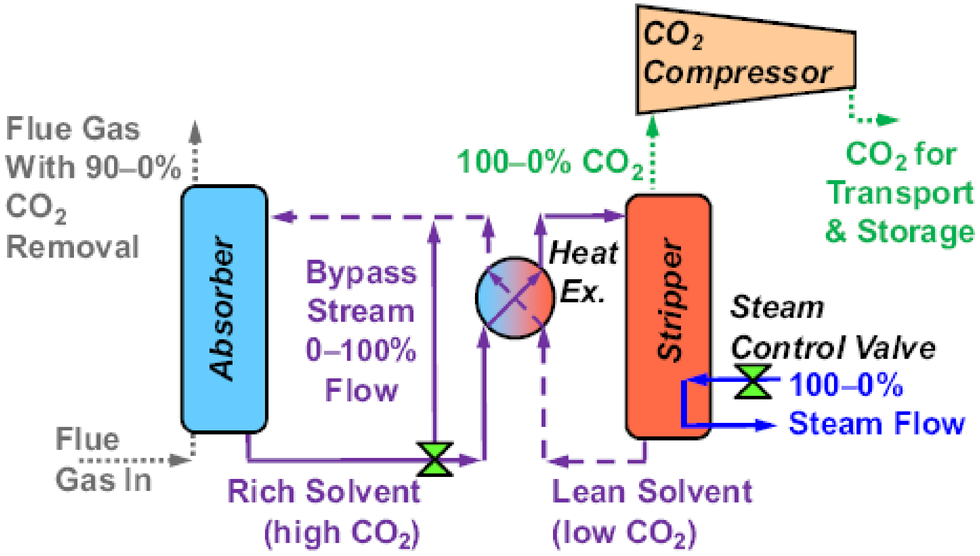
Cohen, S. M., Rochelle, G. T. & Webber, M. E. 2011. *Energy Procedia, 4**, 2604-2611.***

Flexible Operation Strategies

Strategies that improve flexibility:

Solvent storage tanks

Bypass system



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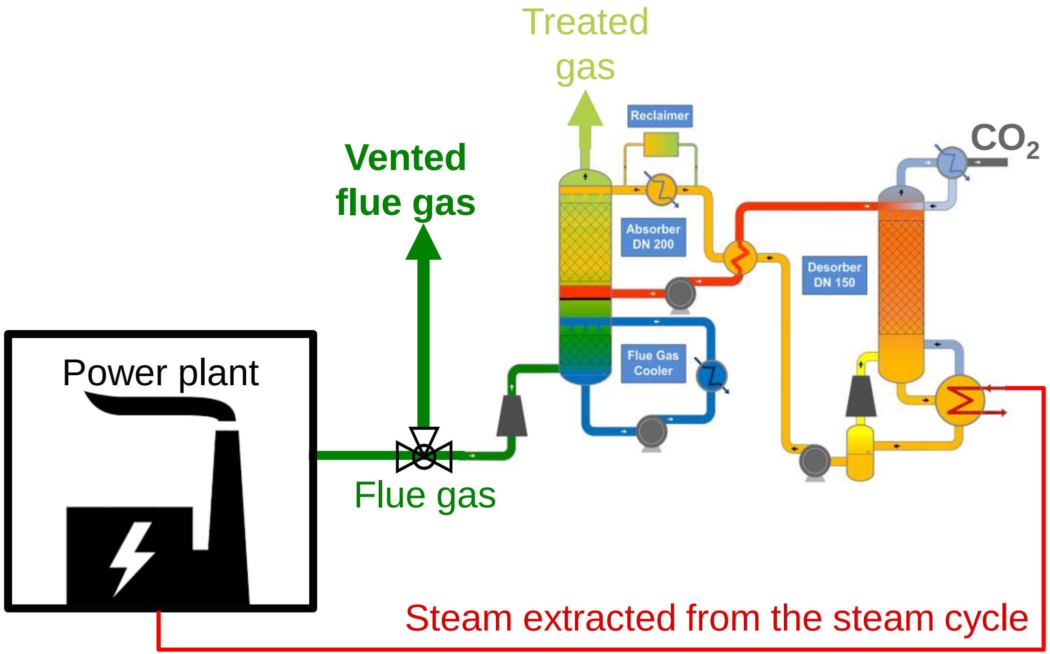
Flexible Operation Strategies

Strategies that improve flexibility:

- Solvent storage tanks
- Bypass system
- Venting system



Wiley, D. E., Ho, M. T. & Donde, L. (2010). Energy Procedia, 4, 1893–1900 (2011).

Flexible Operation Strategies

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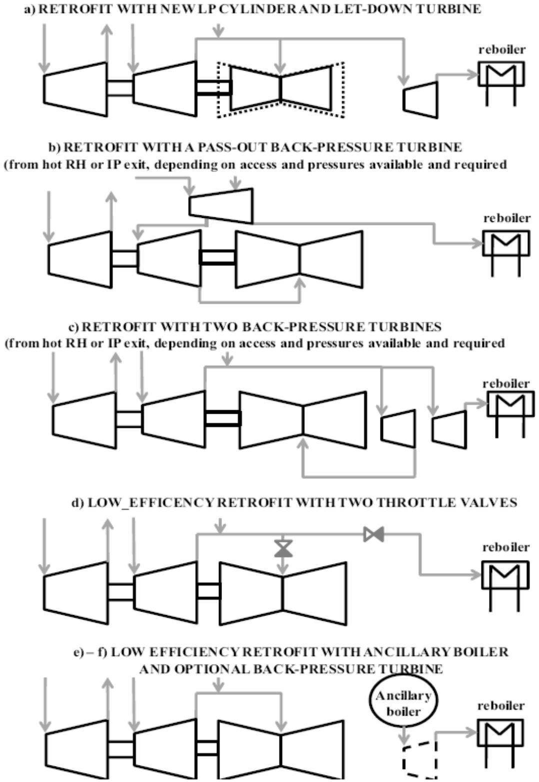
Strategies that improve flexibility:

- Solvent storage tanks
- Bypass system
- Venting system
- Optimised steam cycle design



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Flexible Operation Strategies

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Strategies that improve flexibility:

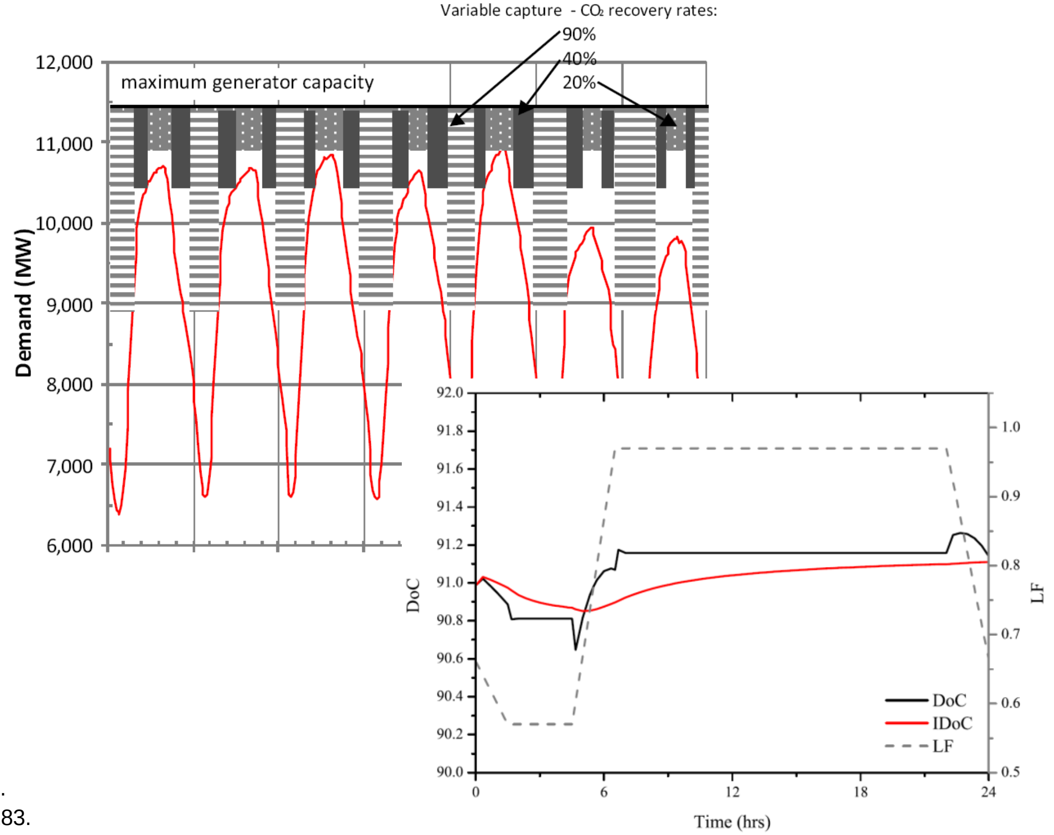
Solvent storage tanks

Bypass system

Venting system

Optimised steam cycle design

Load following



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Flexible Operation Strategies

Strategies that improve flexibility:

- Solvent storage tanks
- Bypass system
- Venting system
- Optimised steam cycle design
- Load following
- Time-varying solvent regeneration

Mac Dowell, N. & Shah, N. (2015). Computers & Chemical Engineering, 74, 169–183.

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Time-varying solvent regeneration

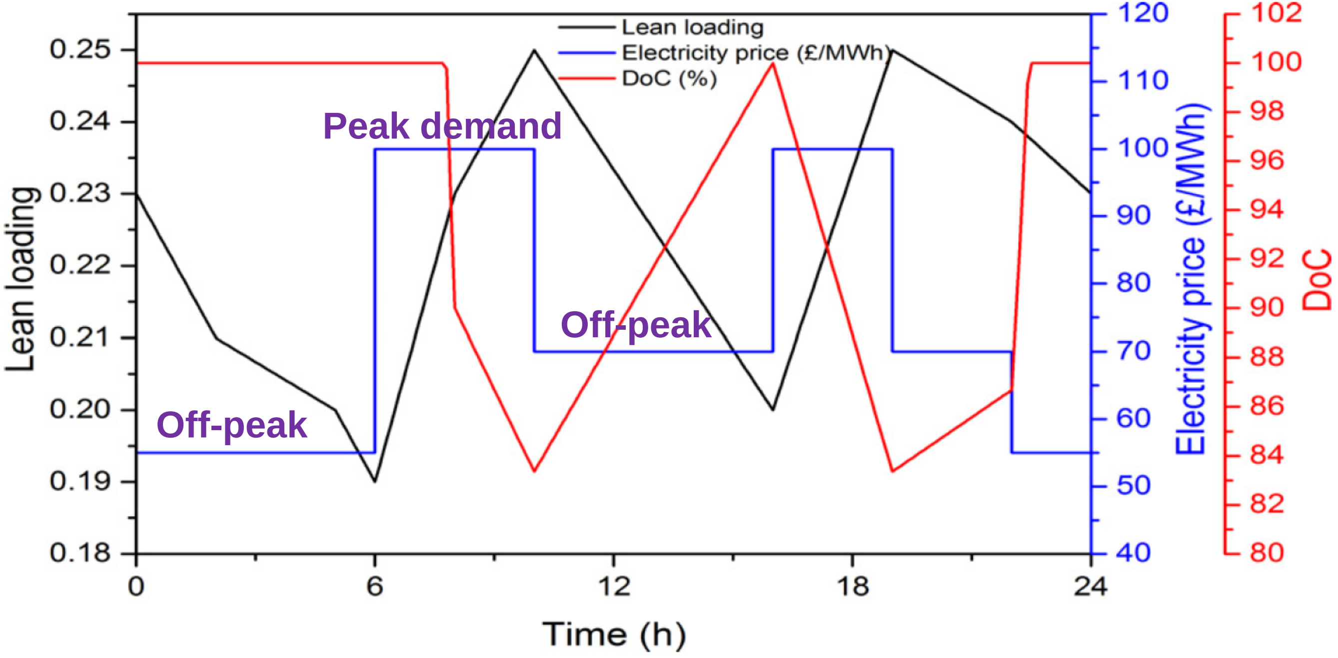
The use of solvent storage tanks involves high capital cost.

Alternatively, CO_2 can be "stored" within the amine liquid.

The **time-varying solvent regeneration** approach can be used to coordinate the DoC with electricity price/demand.

Potentially more cost effective and profitable.

Combined cycle gas turbine power plant



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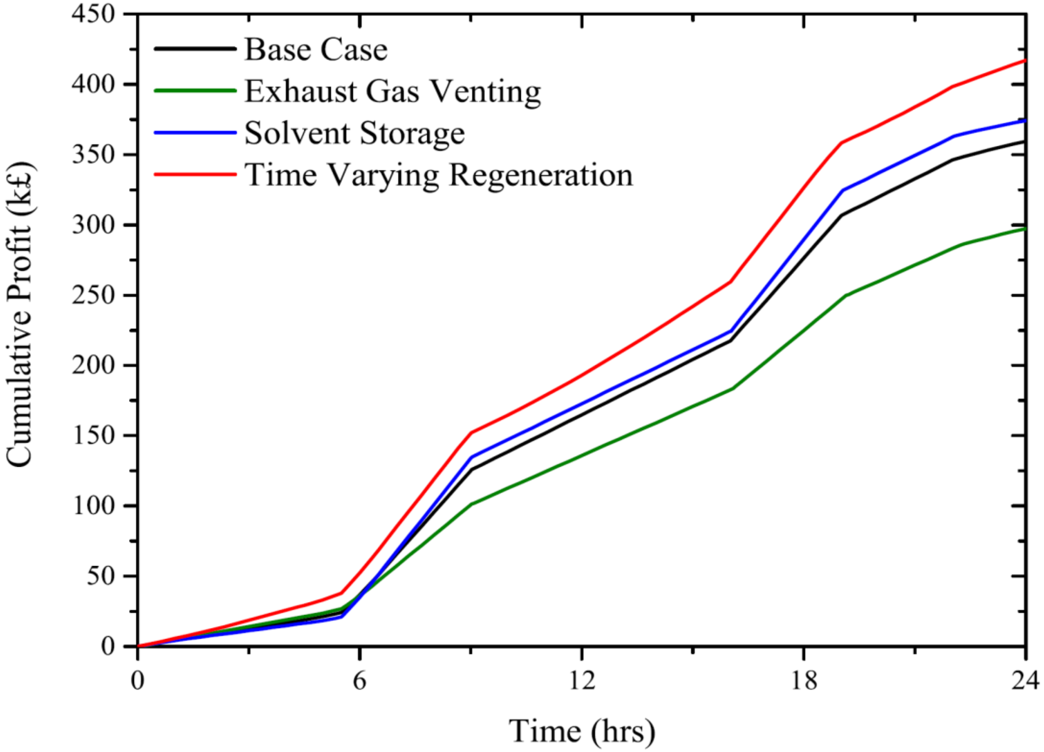
Time-varying solvent regeneration

Time-varying solvent regeneration looks to be the most profitable strategy.

Can we actually do it?



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Process dynamics of flexible operation

Much of the research on flexible operation focuses on the development of operation strategies and configurations.

To design robust flexible operation strategies and process control, we need better understanding of process dynamics at larger plant scales.

This study combines experimental pilot plant testing with dynamic modelling of the TCM CO_2 capture plant.

Objective: To assess the feasibility of novel flexible operation strategies at the TCM CO_2 capture plant (time-varying solvent regeneration, variable ramp rates). Understand the effects of plant scale on the process dynamics.

Bui, M., *et al.* (accepted). Demonstrating flexible operation of the Technology Centre Mongstad (TCM) CO_2 capture plant. International Journal of Greenhouse Gas Control.

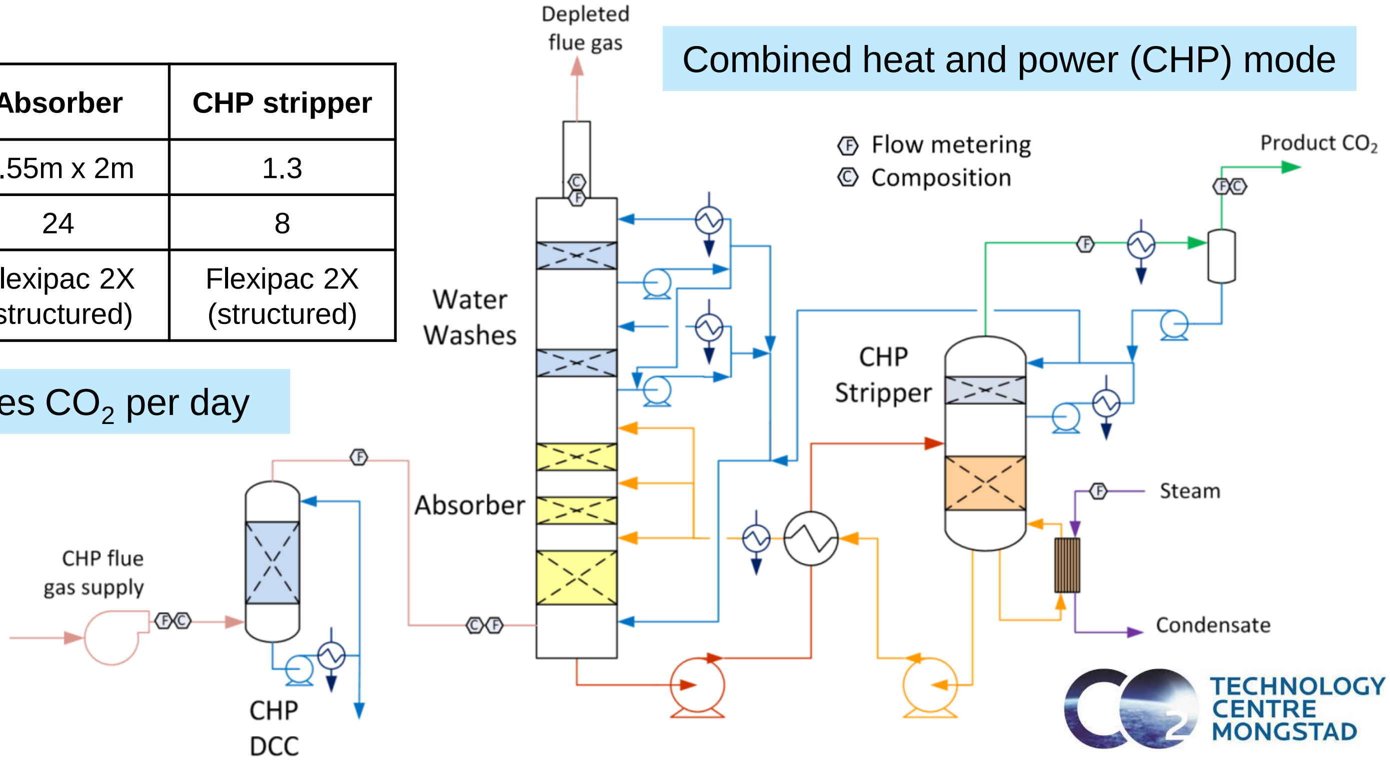
TCM CO_2 capture facility, Mongstad Norway

	Absorber	CHP stripper
Cross section dimensions	3.55m x 2m	1.3
Packing height (m)	24	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



Refinery catalytic cracker (RCC) mode captures 200 t_{CO2}/day, gas CO_2 content 12.9 mol%

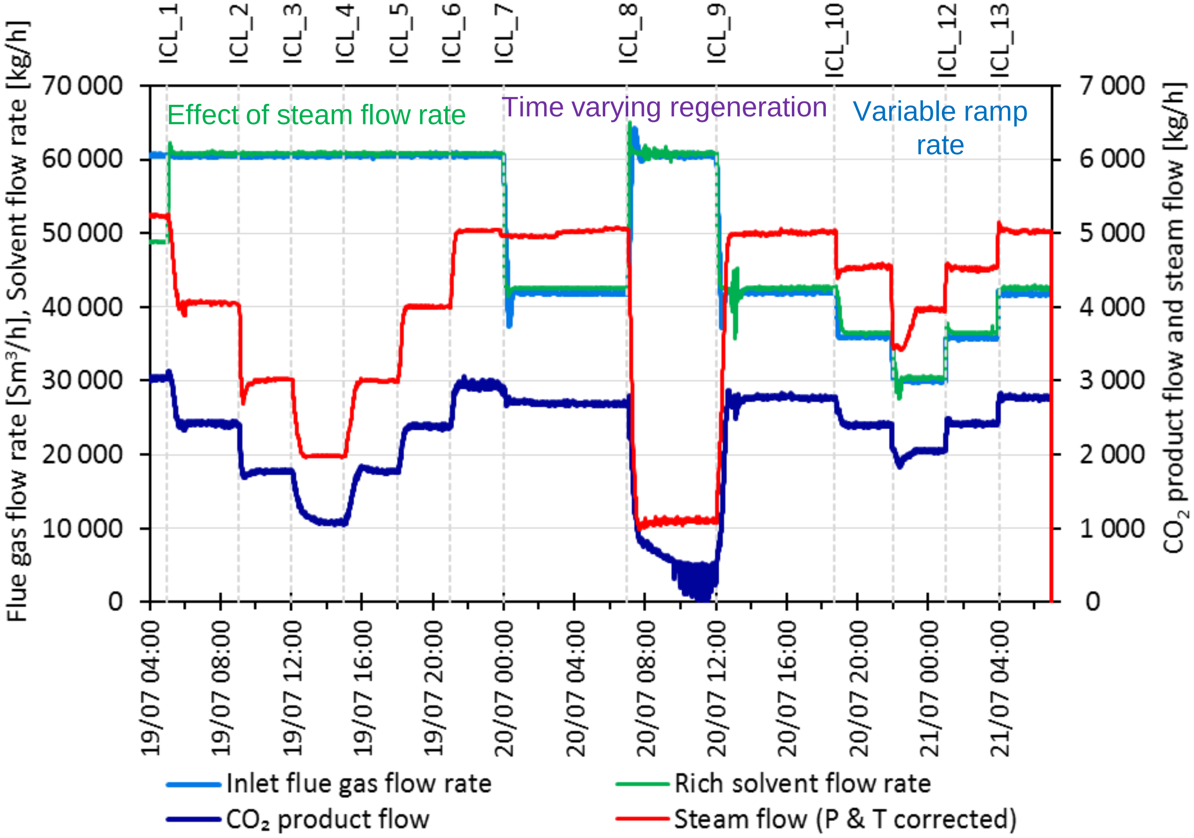
Flexible operation of the TCM CO_2 capture plant

The dynamic operation scenarios of this test campaign are:

Effect of steam flow
ICL_1 to ICL_6

Time-varying solvent regeneration
ICL_7 to ICL_9

Variable ramp rate
ICL_10 to ICL_13



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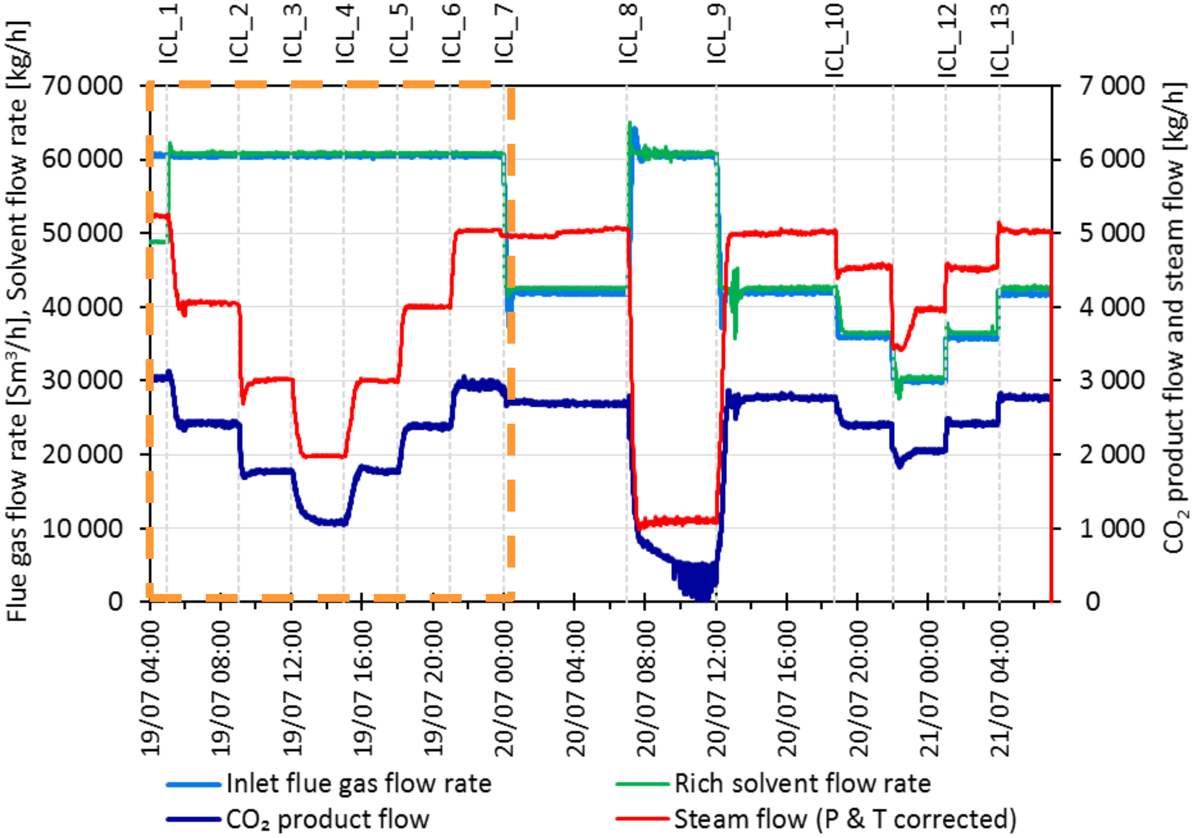
Effect of steam flow rate

To understand the dynamics of the process, the relationship between steam flow rate and the degree of capture was establish.

Steam flow rate (kg/h)	CO_2 capture rate (%)	Lean CO_2 loading (mol $_{CO2}$/ mol $_{MEA}$)
2000	**26.0**	**0.4375**
5000	**72.0**	**0.2456**



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Time-varying solvent regeneration

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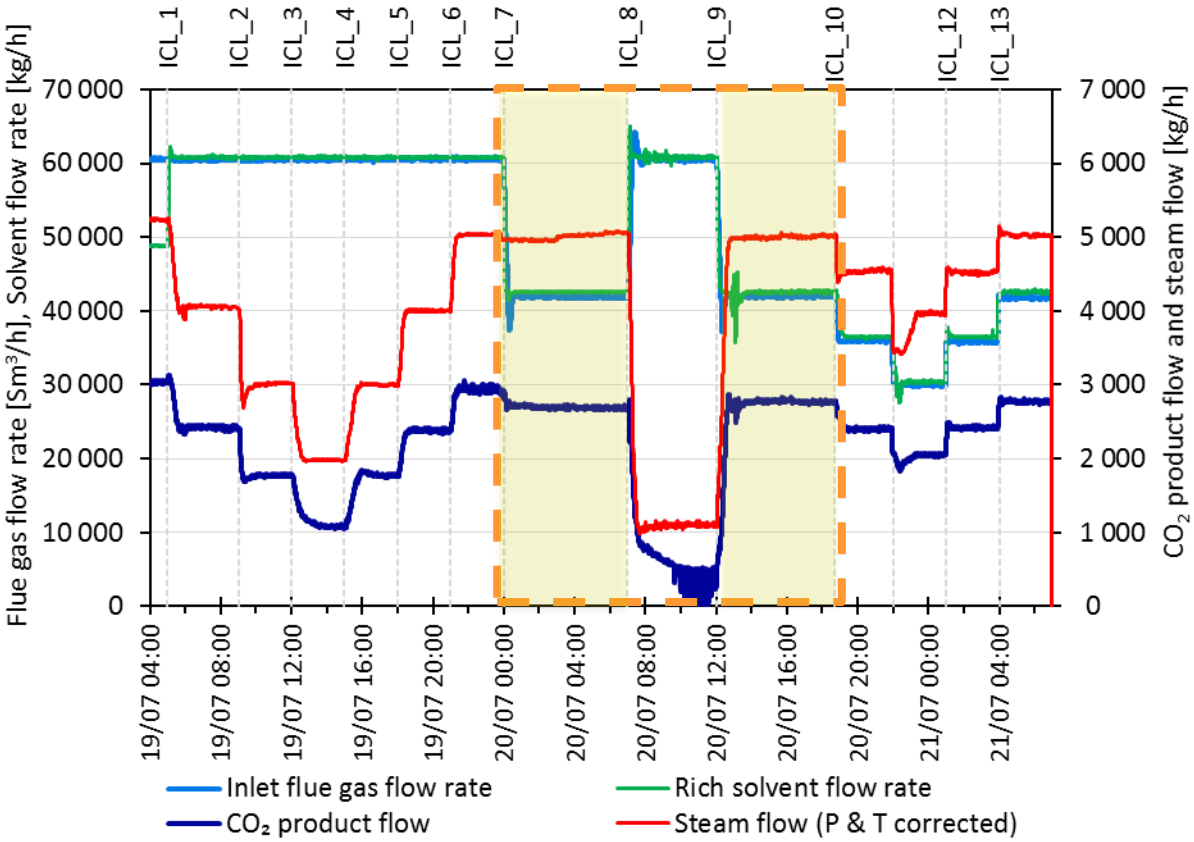
Off-peak electricity prices: Solvent is regenerated, reducing power output → expect lower flue gas flow rates.

Increase steam flow to reboiler:

- Increases degree of capture (DoC)
- Decreases lean CO_2 loading

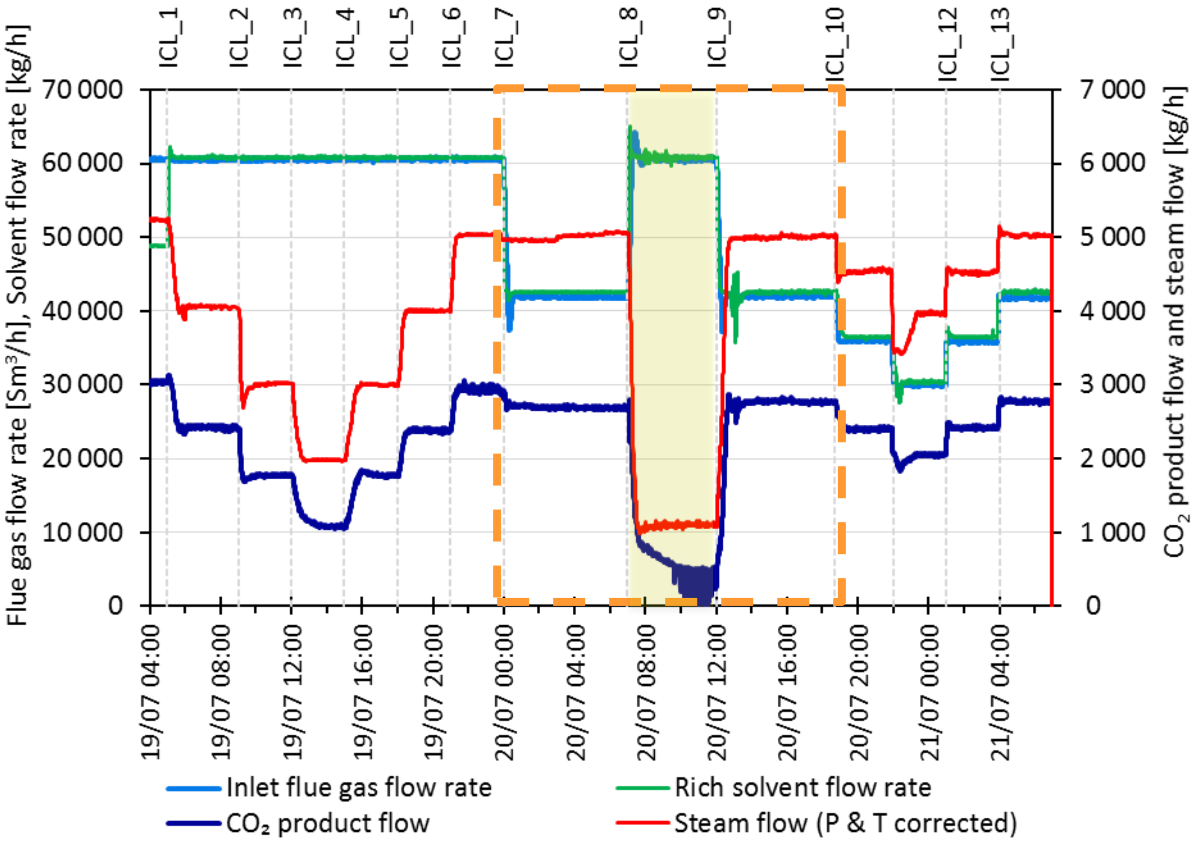


Time-varying solvent regeneration

Peak electricity prices: accumulate CO_2 in the amine

Power output increases, burning more fuel → higher flue gas flow rates.

Reduce steam flow to reboiler:
- DoC reduces
- Increase in lean CO_2 loading



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}

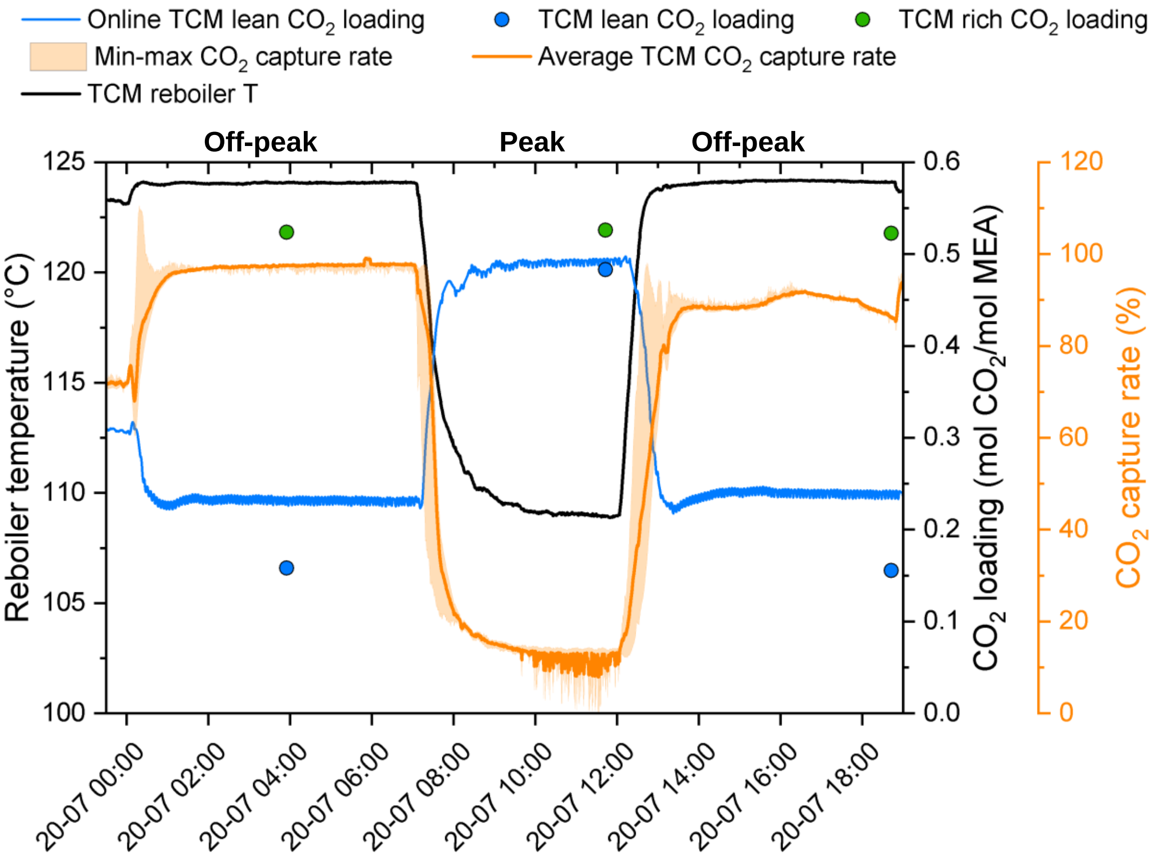
***Peak:** CO_2 is "stored" in solvent and lean CO_2 loading increases.*

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

<u>Cumulative</u> CO_2 capture rate: 66.5%



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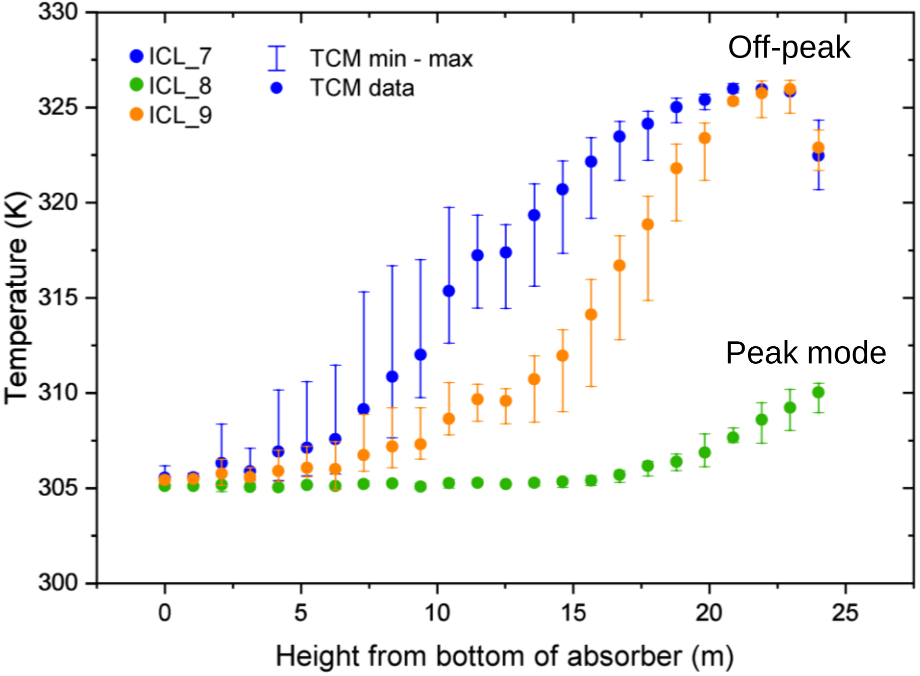
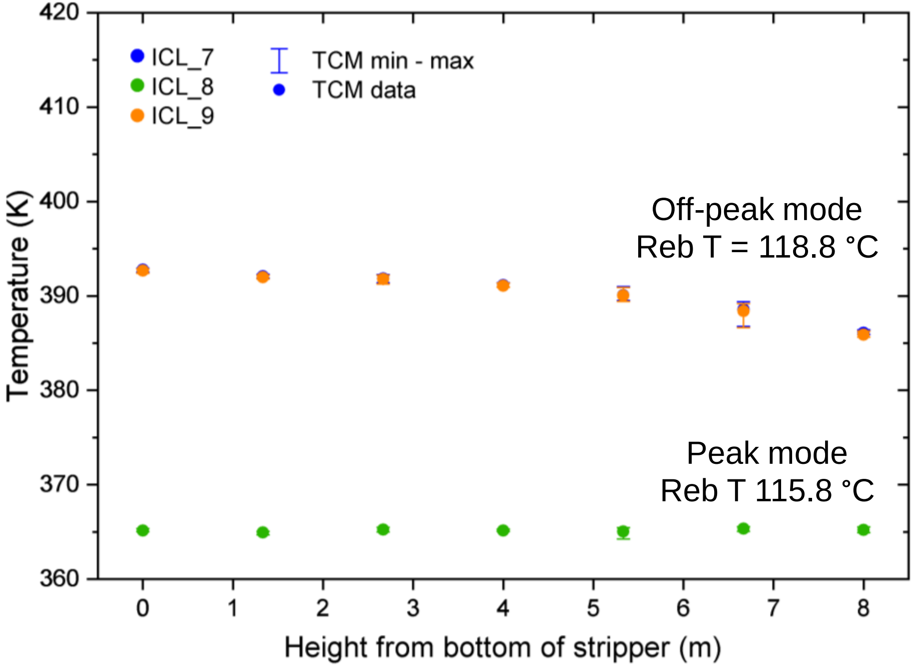
Time varying solvent regeneration

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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Variable ramp rate

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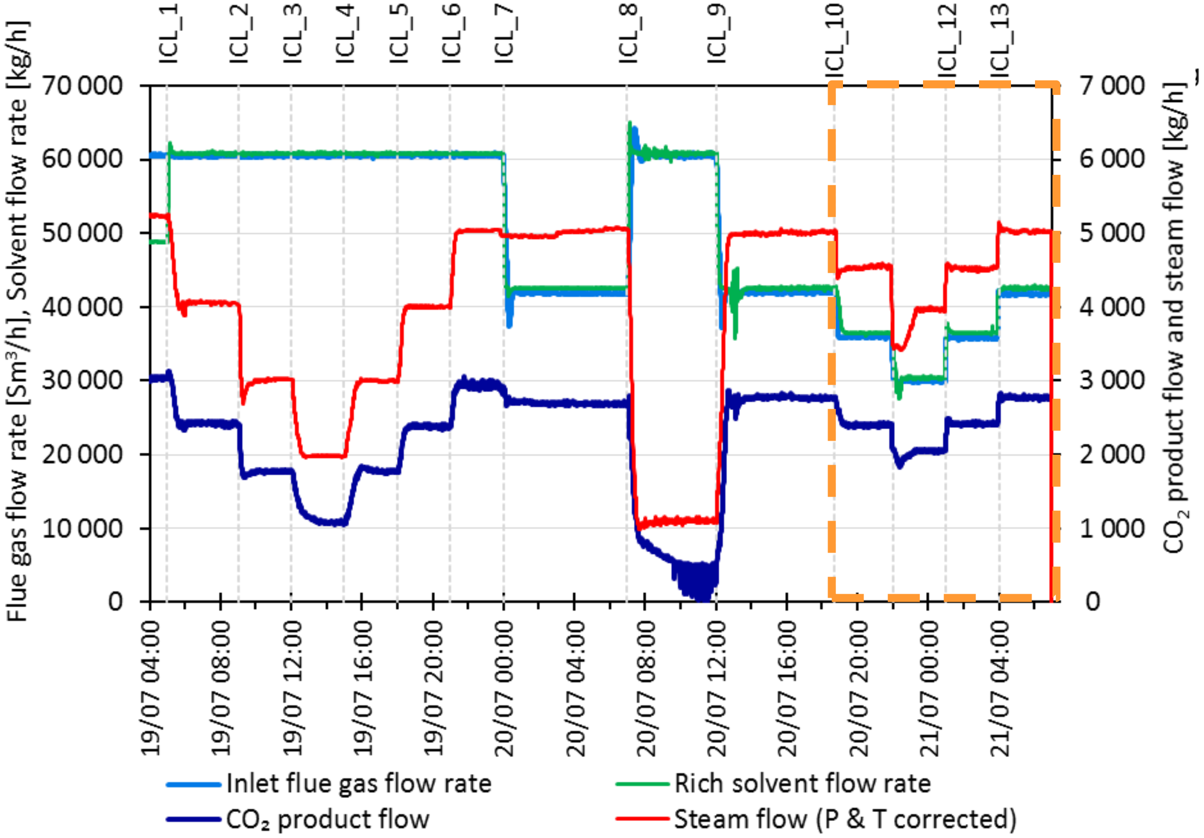
Can the CO_2 capture plant be as flexible as the power plant?

Conventional CCGT can ramp at 2–8 %P_n/min[1]

Ramp rates tested:
1) decrease 0.6%/min
2) decrease 0.6%/min
3) increase 1.7%/min
4) increase 5%/min

The process control system at TCM limits ramp rate to 0.6%/min. Manual operation of blower enables ramp rates 1.7 to 5%/min.



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[1] Hentschel, J., Babić, U. a. & Spliethoff, H. (2016). Energy Reports, 2, 40–47.

Variable ramp rate

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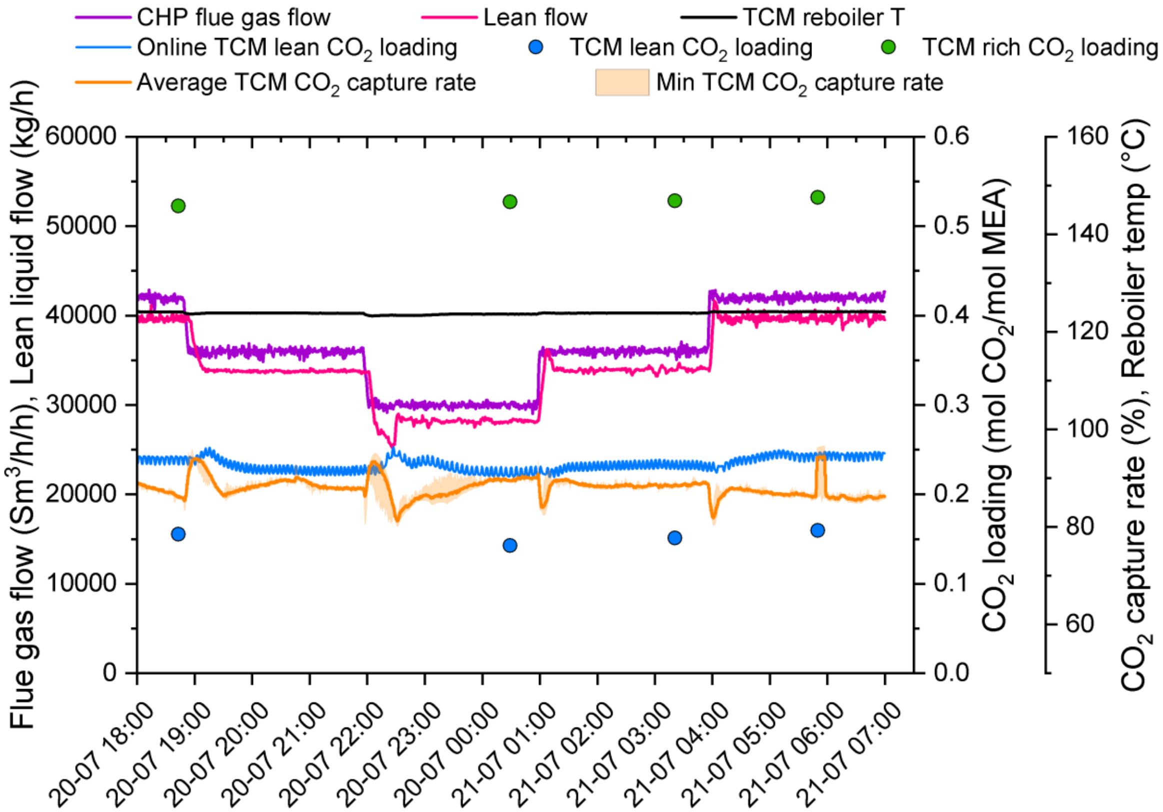
Flue gas, solvent and steam flow rates ramped simultaneously, maintaining constant L/G ratio.

CO_2 capture rate: 87–89%
Lean CO_2 loading:
0.14–0.16 mol CO_2/mol MEA
Rich CO_2 loading:
~0.53 mol CO_2/mol MEA

By keeping L/G ratio constant, the CO_2 capture performance also remains constant:

- lean CO_2 loading
- rich CO_2 loading
- CO_2 capture rate



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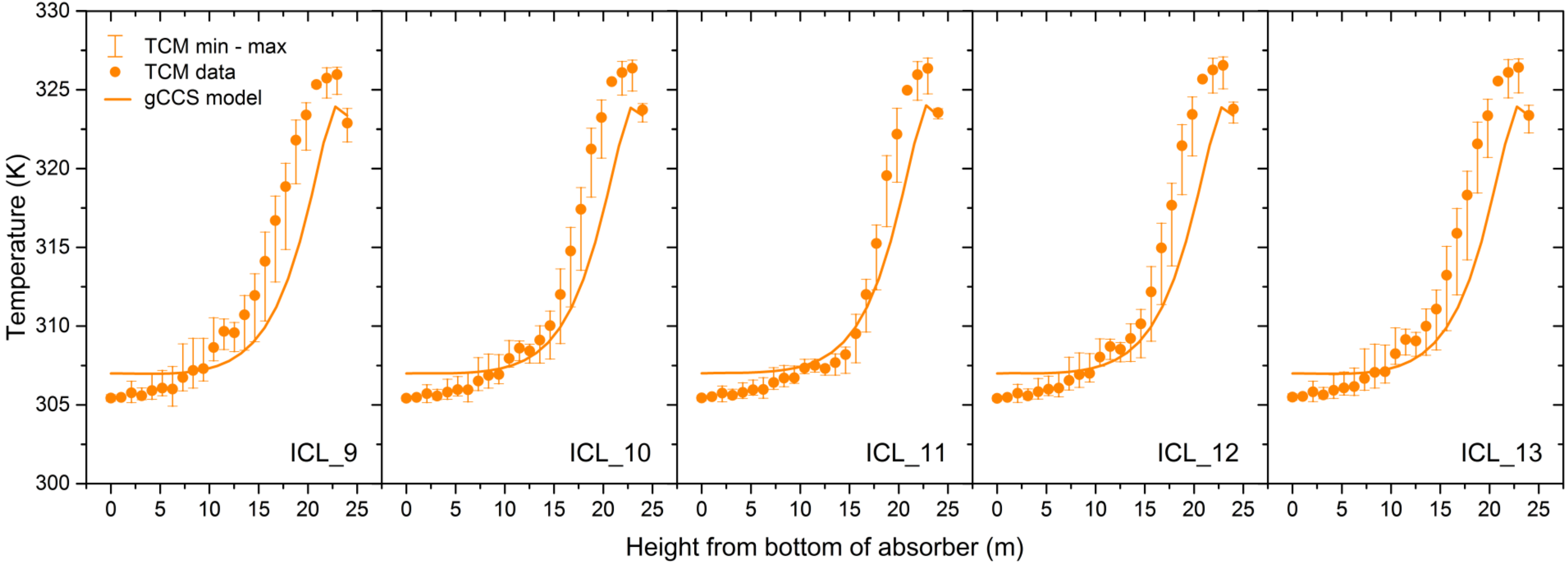
Variable ramp rate: Absorber temperature

↓ 0.6%/min ramp
FG, solvent & steam flow

↓ 0.6%/min ramp
FG, solvent & steam flow

↑ 1.7%/min ramp
FG, solvent & steam flow

↑ 5%/min ramp
FG, solvent & steam flow



Ramp flows + L/G constant → Constant CO_2 capture rate → Constant Absorber T

Bui, M., *et al.* (accepted). Demonstrating flexible operation of the Technology Centre Mongstad (TCM) CO_2 capture plant. International Journal of Greenhouse Gas Control.

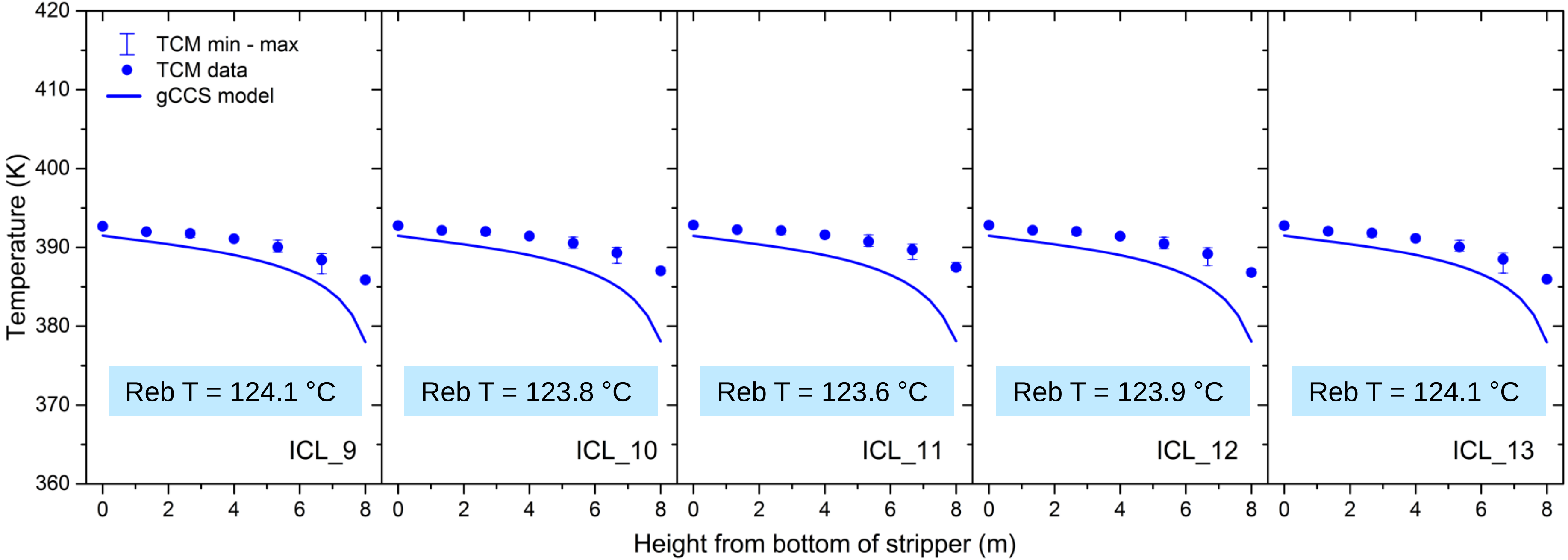
Variable ramp rate: Stripper temperature

↓ 0.6%/min ramp
FG, solvent & steam flow

↓ 0.6%/min ramp
FG, solvent & steam flow

↑ 1.7%/min ramp
FG, solvent & steam flow

↑ 5%/min ramp
FG, solvent & steam flow



Change in steam flow rate not significant enough to result in large change in Reb T → Stripper T constant

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Conclusions

This study demonstrates that flexible operation is technically feasible in a CO_2 capture process using MEA in the TCM CO_2 capture plant (captures 80 t_{CO2}/day in CHP mode).

Understanding the dynamics of the process is important when investigating flexible operation strategies, *e.g.*, effect of only changing steam flow rate. For example, TCM results show:

Steam flow rate (kg/h)	CO_2 capture rate (%)	Lean CO_2 loading (mol CO_2/ mol MEA)
2000 ⇩	**26.0** ⇩	**0.4375** ⇧
5000 ⇧	**72.0** ⇧	**0.2456** ⇩

Time-varying solvent regeneration: absorption-based processes can "store" CO_2 within the amine liquid – lean loading increases from 0.16 (off-peak) to 0.48 (peak) mol CO_2/mol MEA.

Variable ramp rate: different ramp rates can be applied in succession. By maintaining a constant L/G ratio, CO_2 capture performance (capture % and loading) will remain constant

Bui, M., *et al.* (accepted). Demonstrating flexible operation of the Technology Centre Mongstad (TCM) CO_2 capture plant. International Journal of Greenhouse Gas Control.

Key characteristics found to limit flexibility

Stabilisation time: Need to allow sufficient time to stabilise the plant before changing to new process conditions.

Transition time: For step changes and rapid ramp rates to new set-point conditions, actual process conditions do not transition immediately, it takes time to reach final set-point conditions. This time varies with parameter & size of the change.

Magnitude and speed of process parameter change: Rapid and large process parameter changes tend to be avoided at TCM to prevent inverse responses and plant instability (observed in previous test campaigns).

Process control system: Designed for steady state operation. Found to be the key factor that limited ramping capabilities. This is an important area for future work.

Plant flexibility is a function of the **scale** of the plant and **volume of solvent inventory.**

Bui, M., *et al.* (accepted). Demonstrating flexible operation of the Technology Centre Mongstad (TCM) CO_2 capture plant. International Journal of Greenhouse Gas Control.

Further research challenges

Further work studying plants at other different scales → larger scale, slower dynamics

- Develop a correlation between plant scale and dynamic CO_2 capture performance.
- PACT 1 t_{CO2}/day → Brindisi plant 60 t_{CO2}/day → TCM 80 t_{CO2}/day

Solvent development/design

- Improve fluid flow properties to ensure adequate solvent distribution over the packing.
- Higher working capacities (i.e., more moles of CO_2 per mole of liquid absorbent).

Tool development

- Improve accuracy of commercial software to better model dynamic physical behaviour
- Liquid measurement instruments that **accurately** measure CO_2 loading online.
- Process control strategies that improve operability during flexible operation (e.g. to achieve faster ramp rates).

Integrate flexible CO_2 capture processes into energy system models to identify the value of flexible CCS.