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CleanFaB

Carbon Capture & Storage (CCS)

Mai Bui, Niall Mac Dowell

Centre for Environmental Policy, Imperial College London, United Kingdom
Centre for Process Systems Engineering, Imperial College London, United Kingdom
m.bui@imperial.ac.uk niall@imperial.ac.uk

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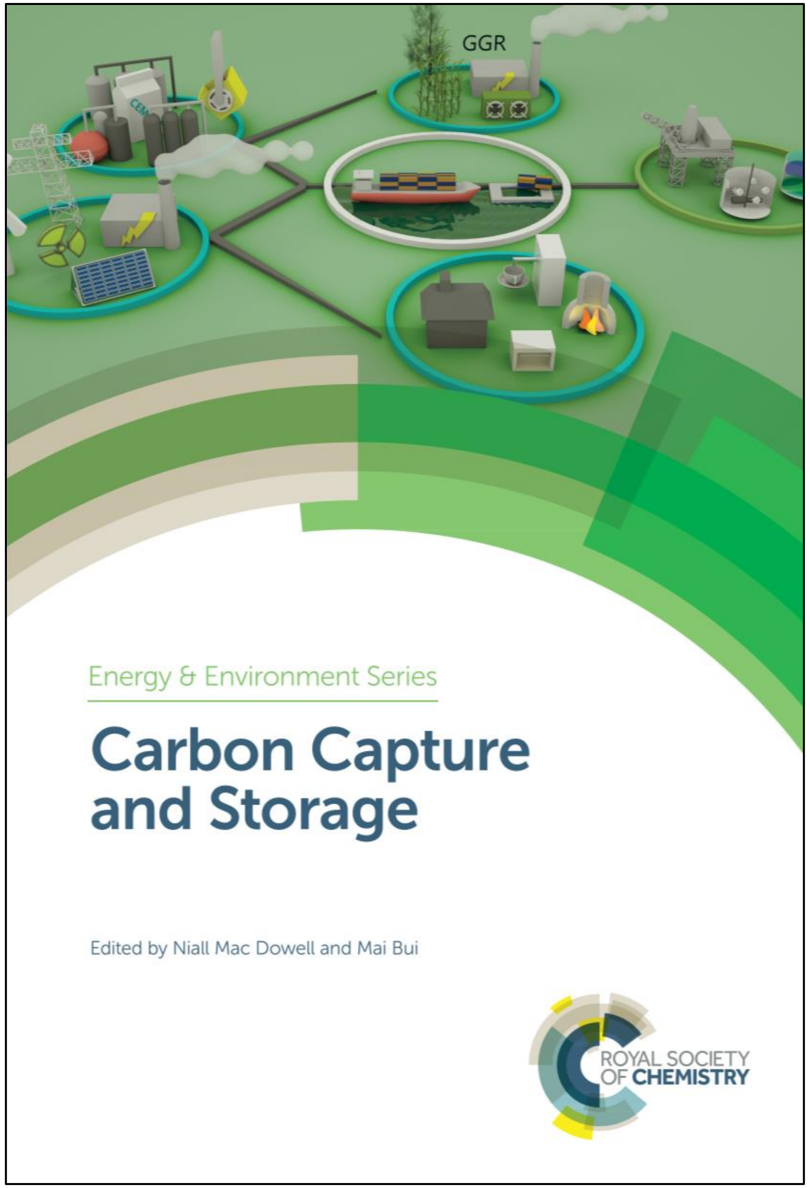
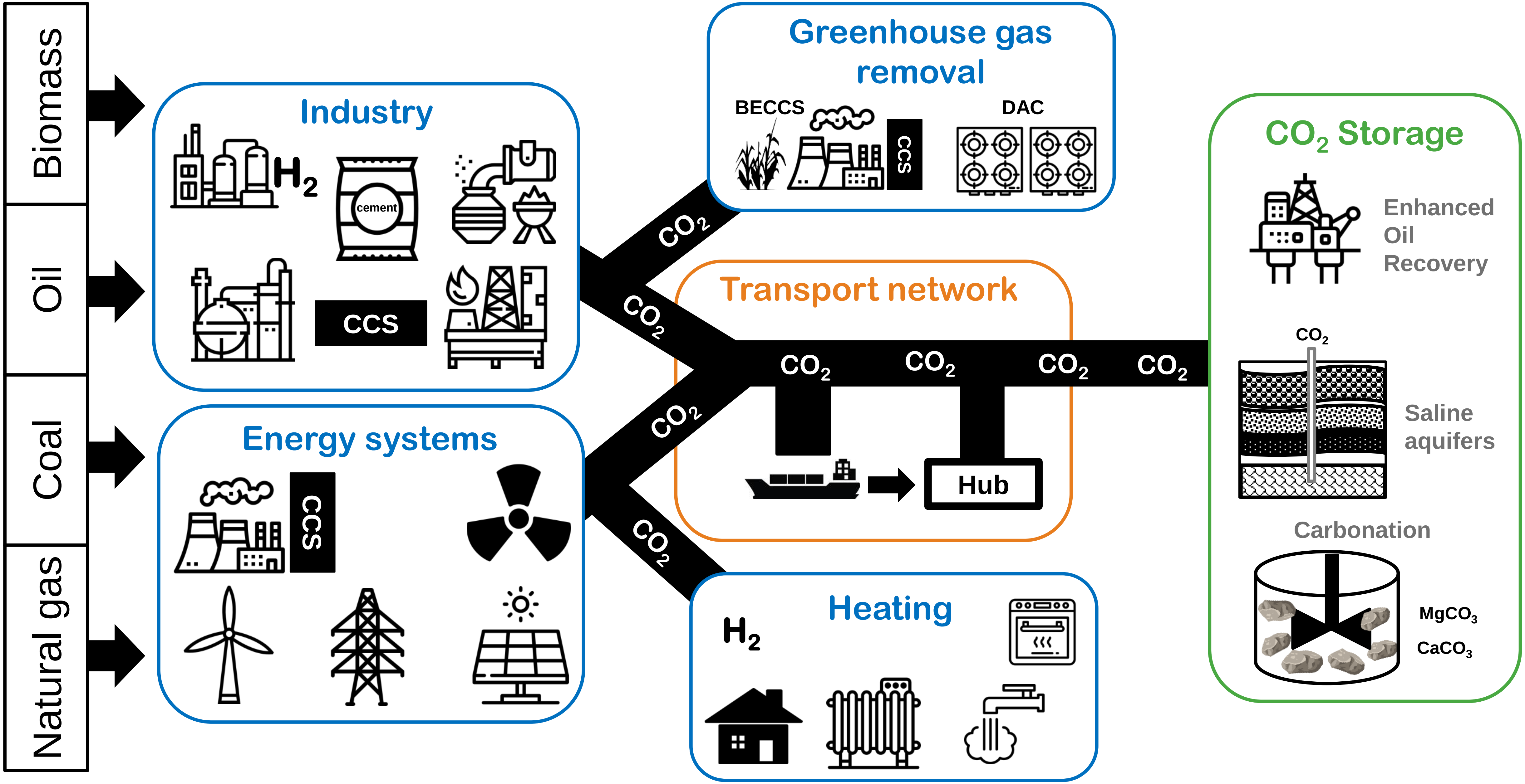


Carbon Capture and Storage (CCS)

1) Introduction
2) Understanding the role of CCS deployment in meeting ambitious climate goals
3) Solvent-based absorption
4) Ionic liquids
5) CO_2 capture by adsorption processes
6) Oxy-fuel combustion capture technology
7) Chemical looping technologies for CCS
8) An introduction to subsurface CO_2 storage
9) Carbon capture and storage from industrial sources
10) Applications of CCS in the cement industry
11) CCS in the iron and steel industry
12) CCS in electricity systems
13) Carbon capture and utilisation
14) Negative emissions technologies
15) New technology development for carbon capture
16) The political economy of carbon capture and storage

Bui, M. & Mac Dowell, N., editors, (2020). Carbon Capture and Storage, Royal Society of Chemistry, UK. https://doi.org/10.1039/9781788012744.


Biomass
Oil
Coal
Natural gas
Industry
H2
cement
CCS
Energy systems
CCS
Greenhouse gas removal
BECCS
CCS
DAC
CO2
CO2
CO2
CO2
CO2
CO2
CO2
CO2
Transport network
Hub
Heating
H2
CO2 Storage
Enhanced Oil Recovery
CO2
Saline aquifers
Carbonation
MgCO3
CaCO3

Role of CCS in the transition to net-zero

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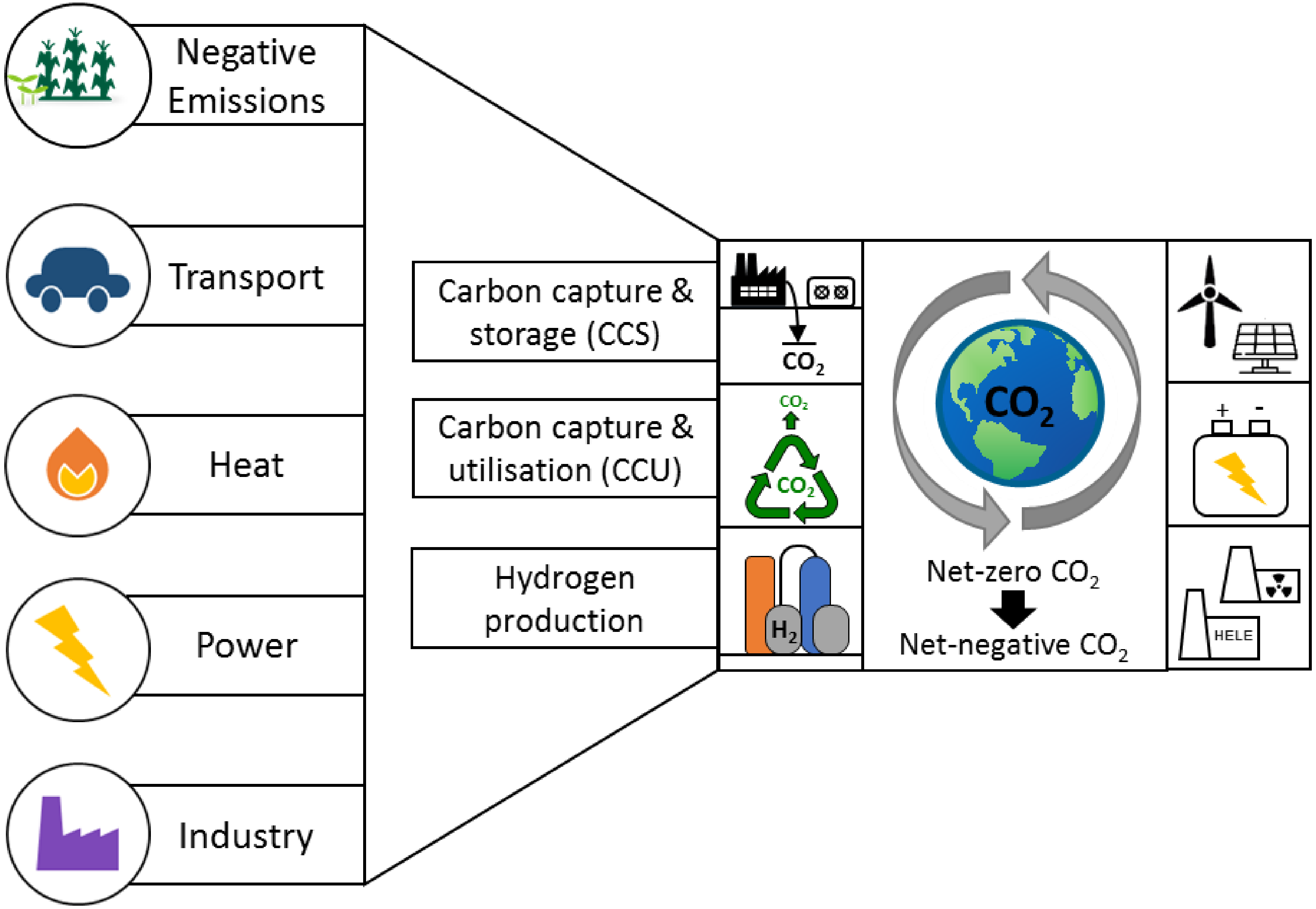
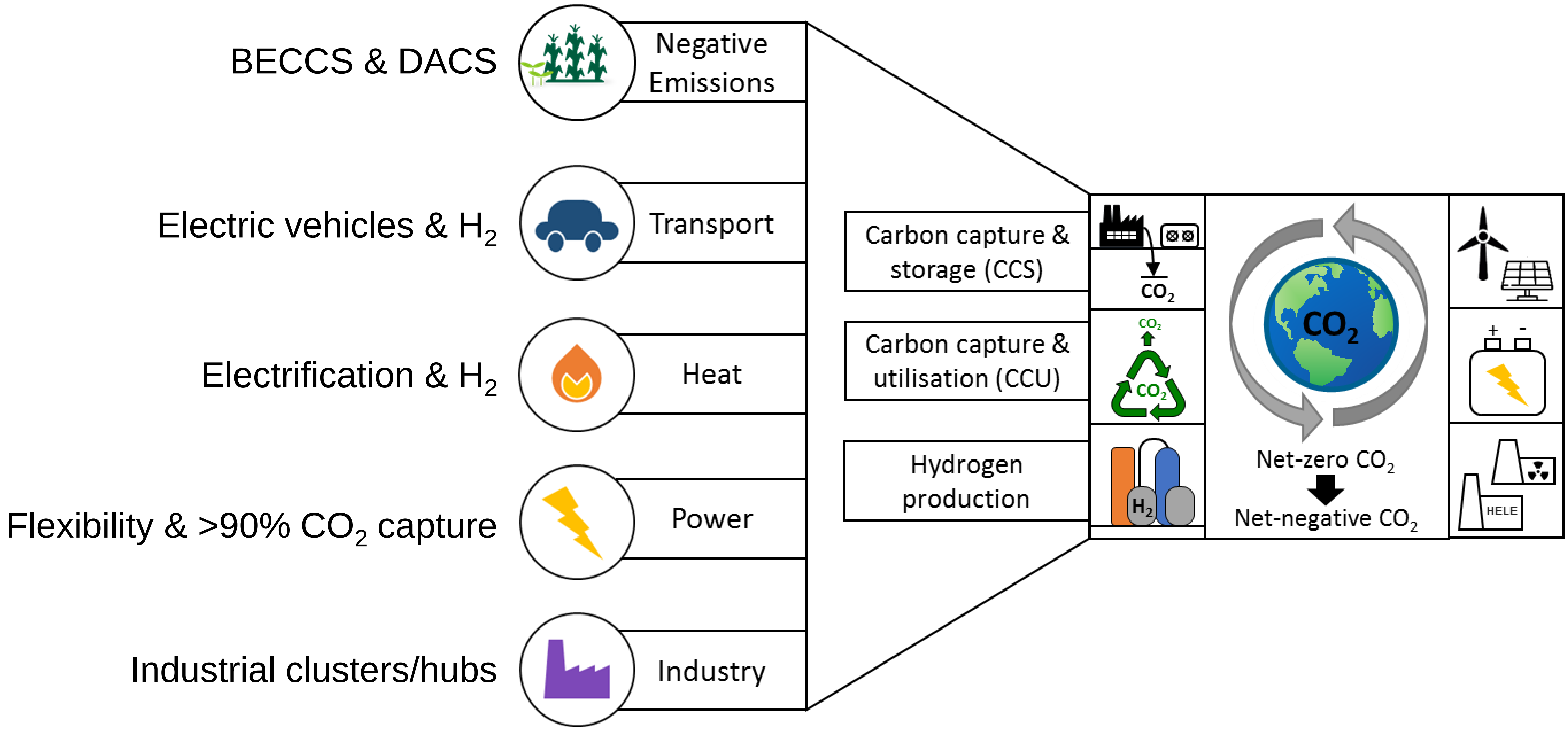
Create and support jobs



Ten Point Plan: https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution

Role of CCS in the transition to net-zero



Global status of commercial scale CCS

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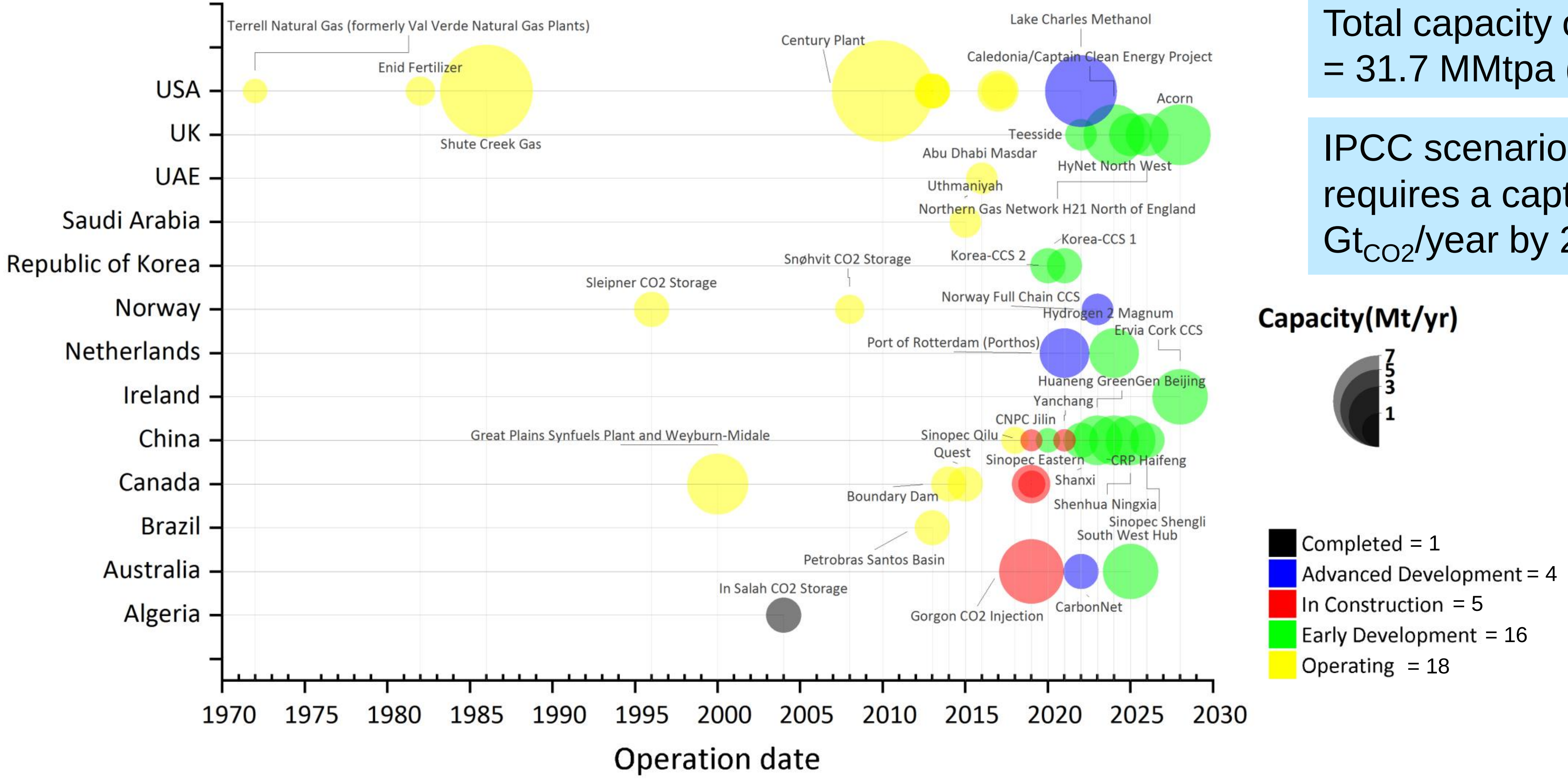

Total capacity of CO_2 captured = 31.7 MMtpa (operating phase)

IPCC scenarios limiting to 2 °C requires a capture rate of ~10 Gt_{CO2}/year by 2050.

Current CCS deployment rate is insufficient to meet the climate change mitigation targets.

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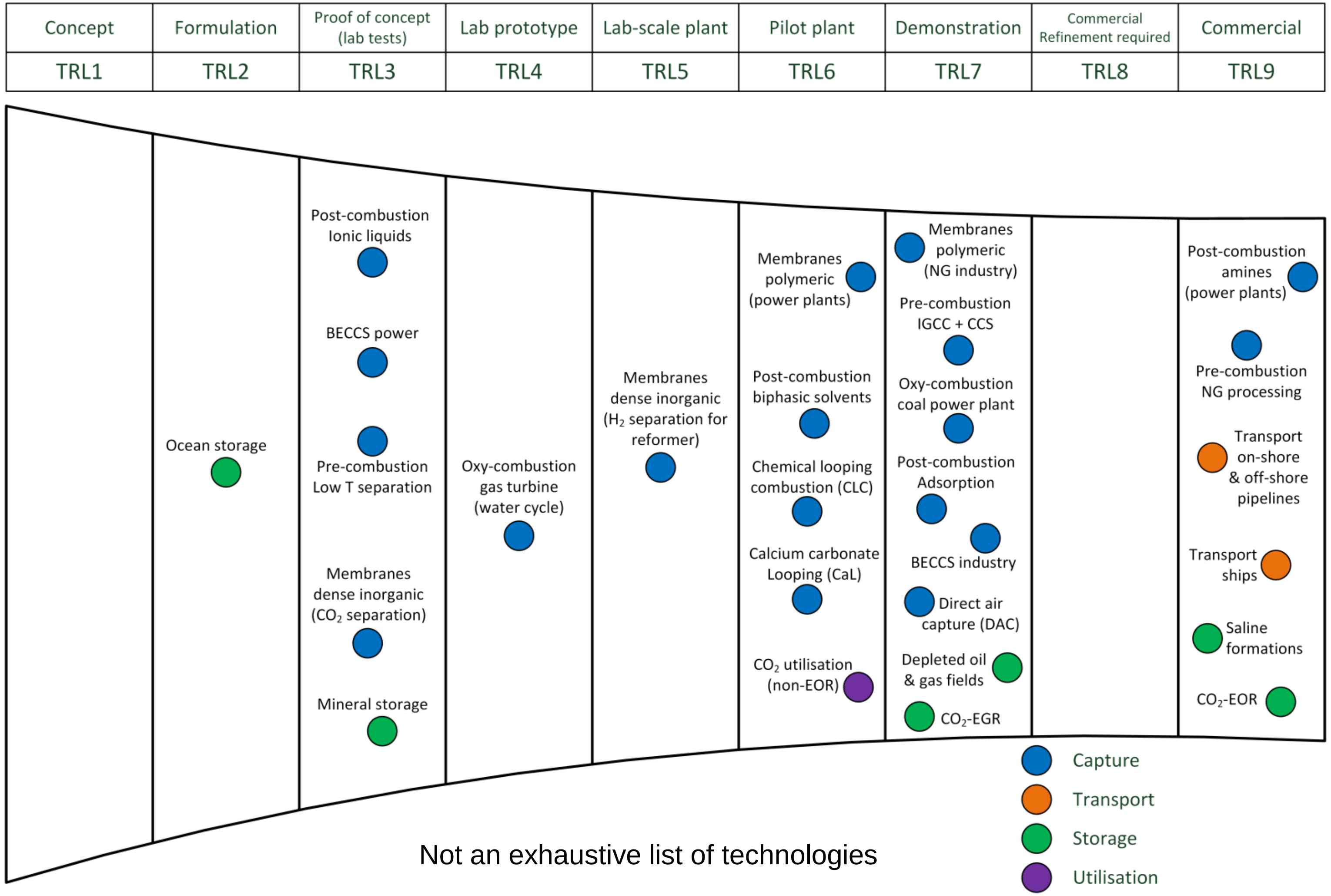
Current status of CCS development



There is a suite of CCS technologies for capture, transport and storage of CO_2.

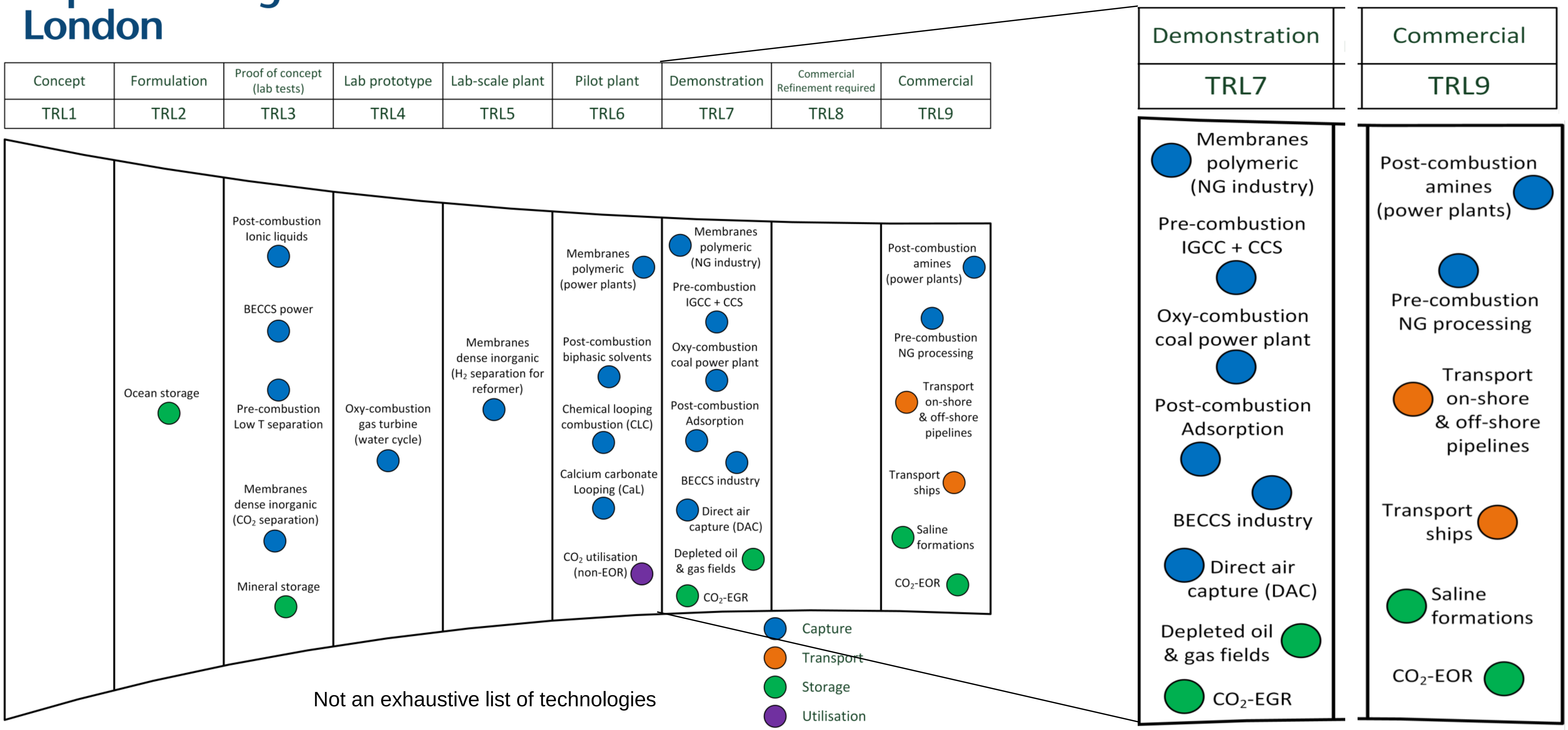
Technologies advance through a series of scale-up steps (lab to commercial scale).

Congestion occurs at TRL 3, TRL 6 & TRL 7.

Development tends to be hindered due to technical challenges or insufficient funding.

Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

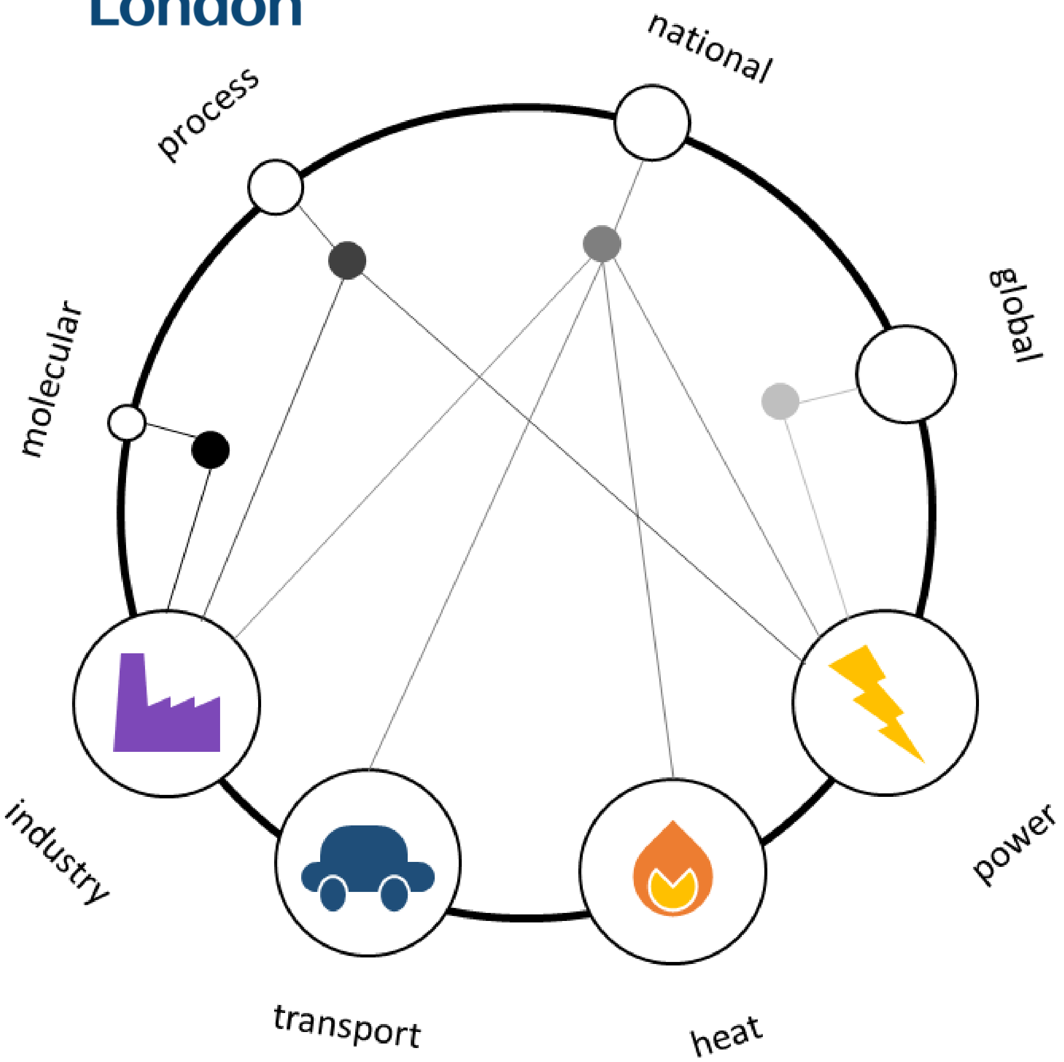
Current status of CCS development

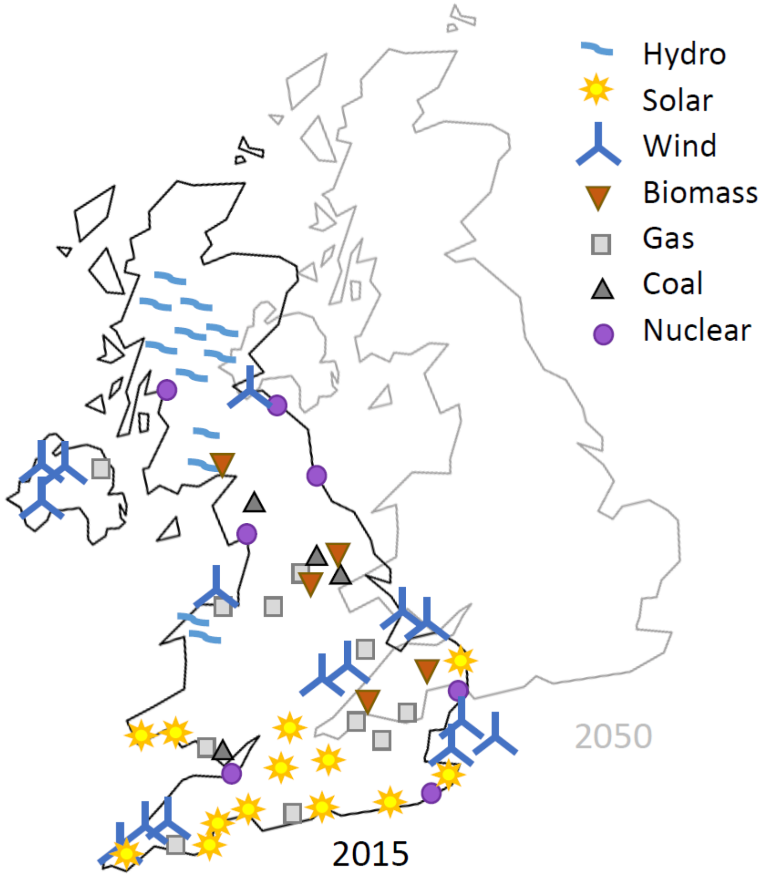


Not an exhaustive list of technologies

Bui et al. (2018). Energy & Environmental Science, 11 (5), 1062-1176.

The transition to net-zero emissions by 2050

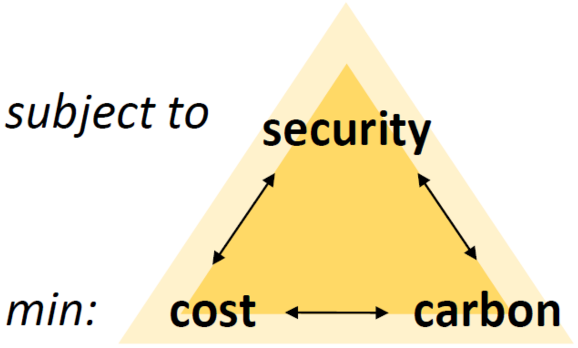




What to build?

Where? When? Why?

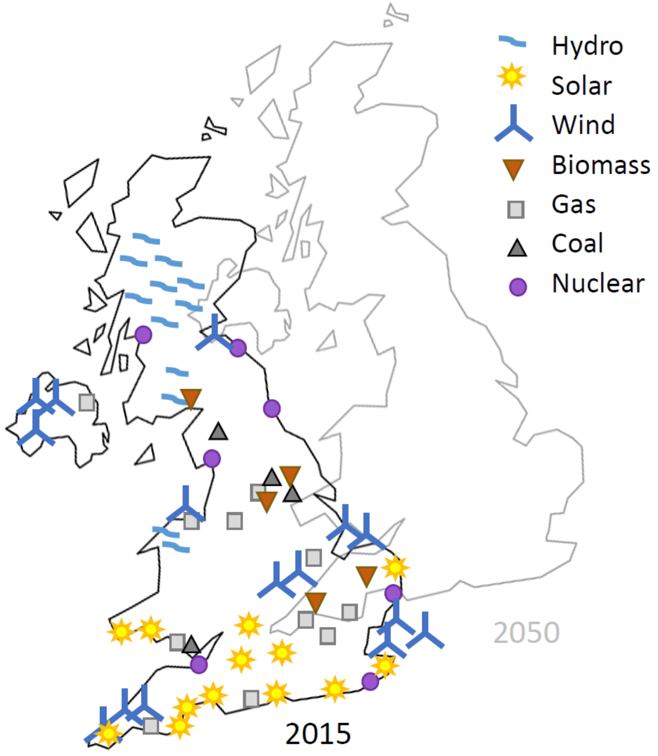
How to operate?

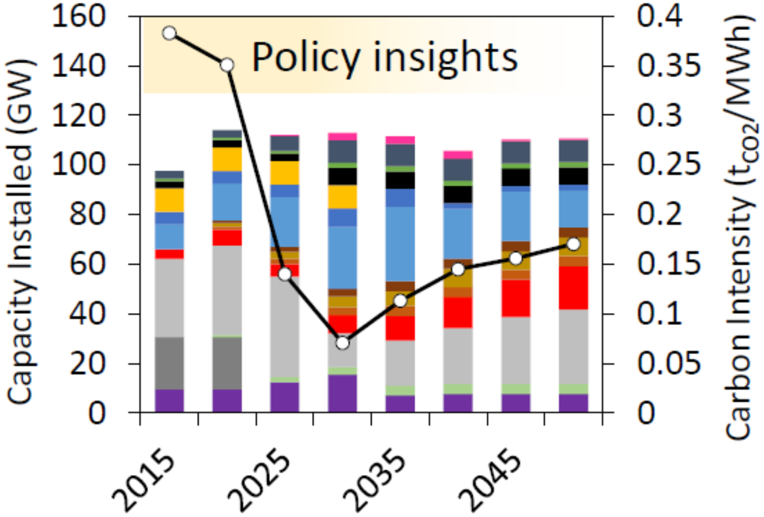


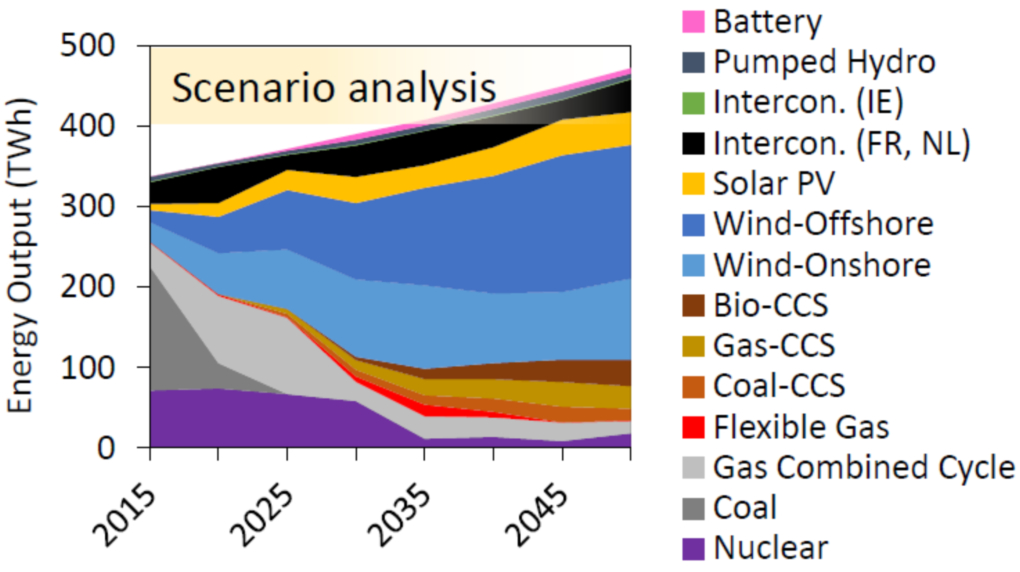
What is the role and value of CCS in the UK energy system?

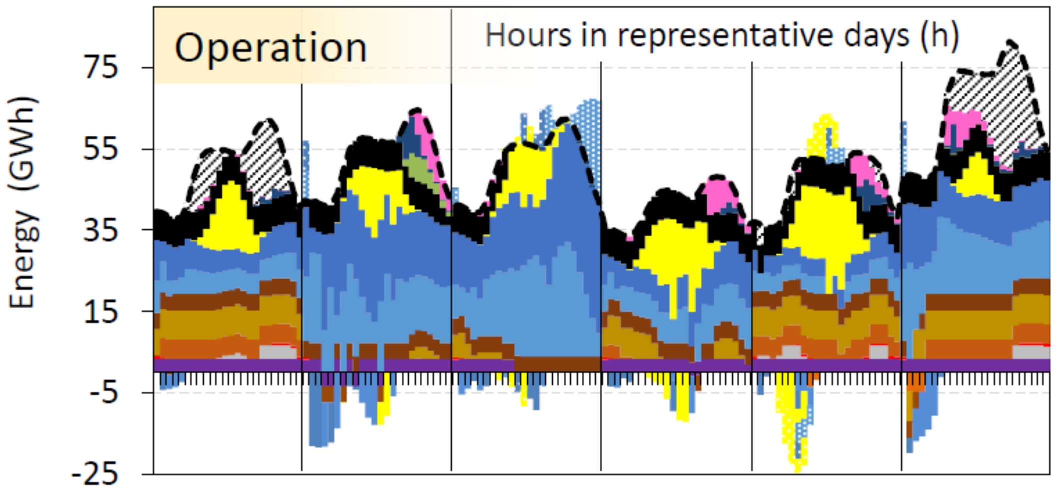
Bui, M. & Mac Dowell, N., editors, (2020). Carbon Capture and Storage, Royal Society of Chemistry, UK. https://doi.org/10.1039/9781788012744.

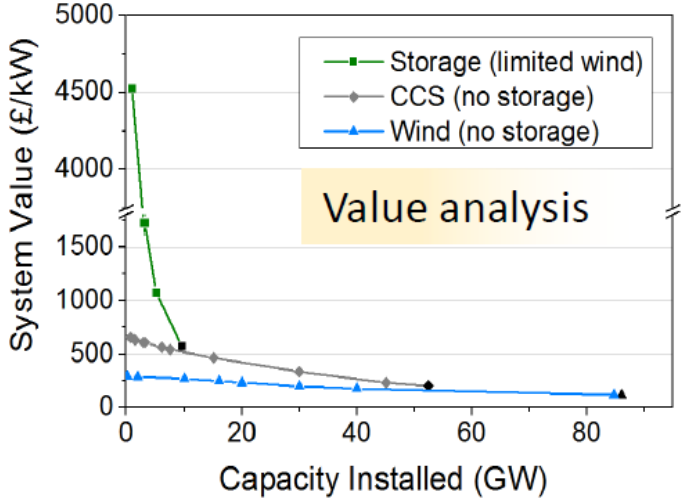
Electricity Systems Optimisation Framework











Heuberger, C. F., et al. (2016). Energy & Environmental Science, 9 (8), 2497-2510.
Heuberger, C. F. & Mac Dowell, N. (2018). Joule, 2 (3), 367-370.
Heuberger, C. F., et al. (2018). Nature Energy, 3 (8), 634-640.

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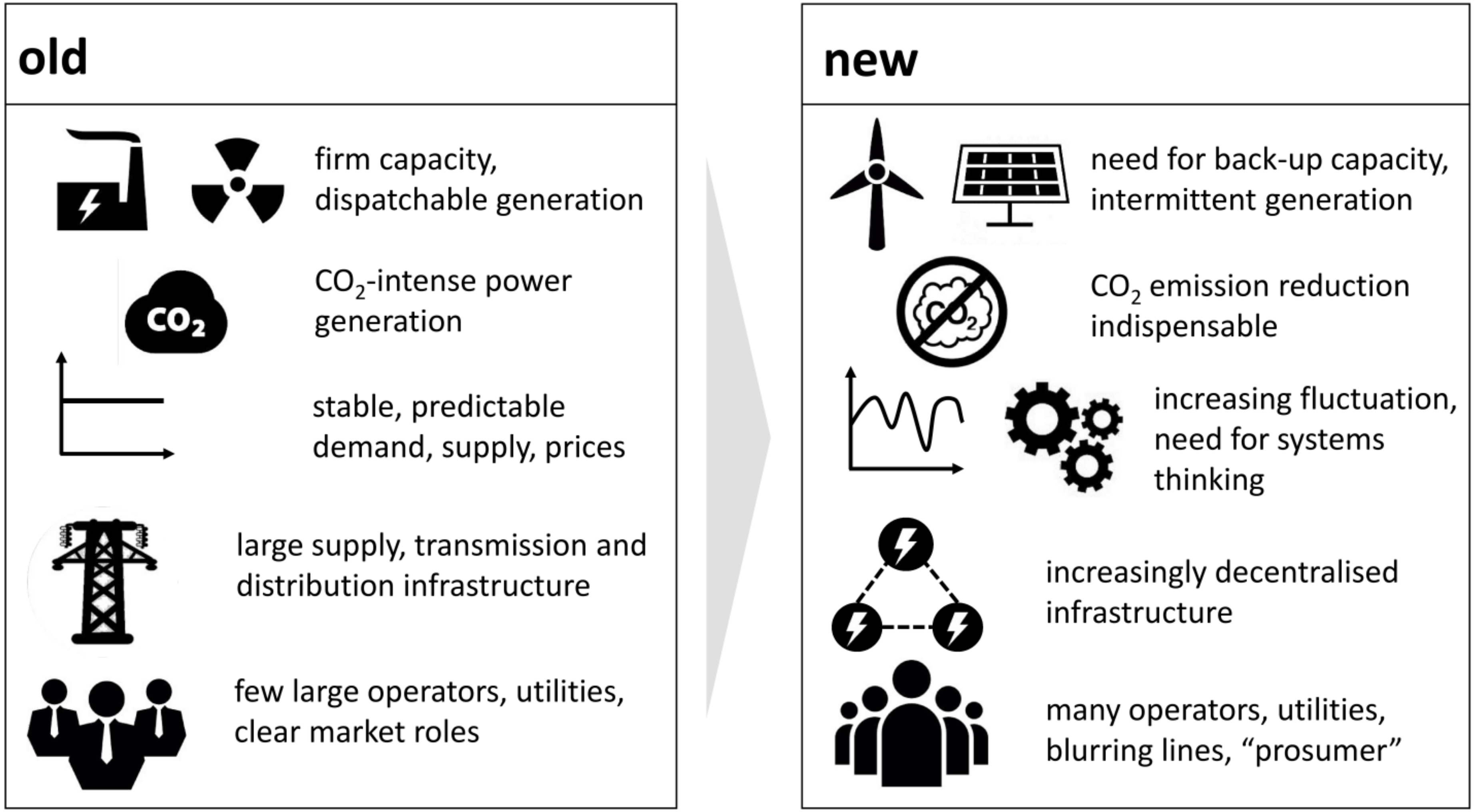
The transition to net-zero in energy systems



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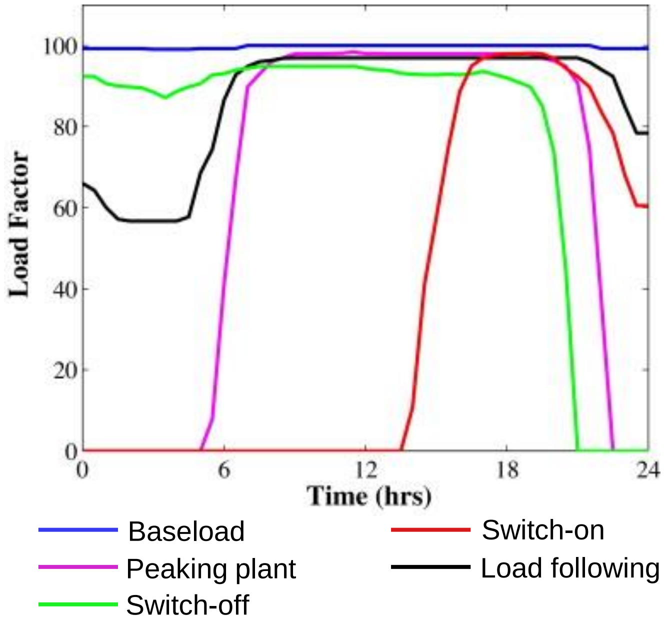
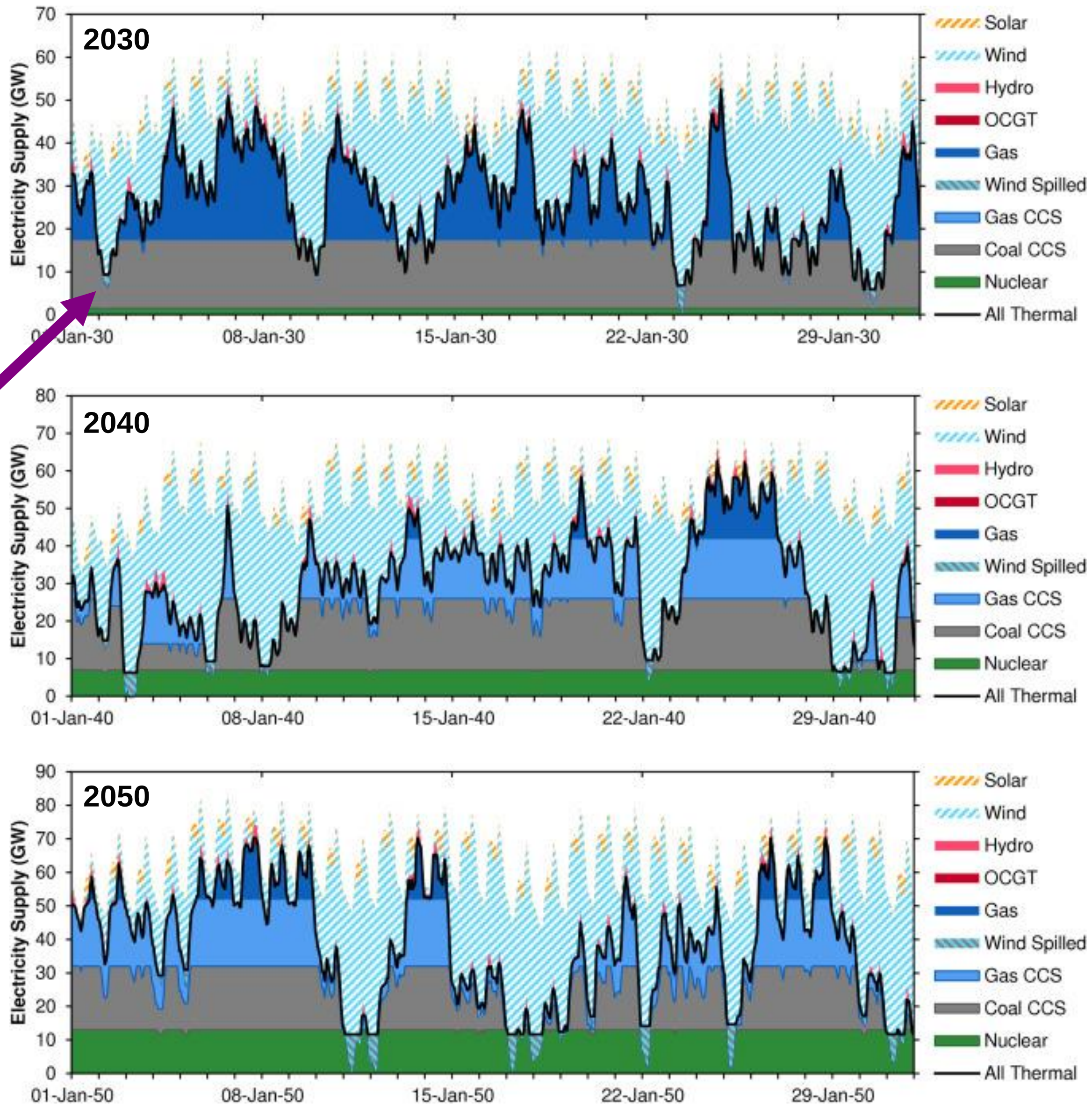
Flexible CCS in future electricity systems

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

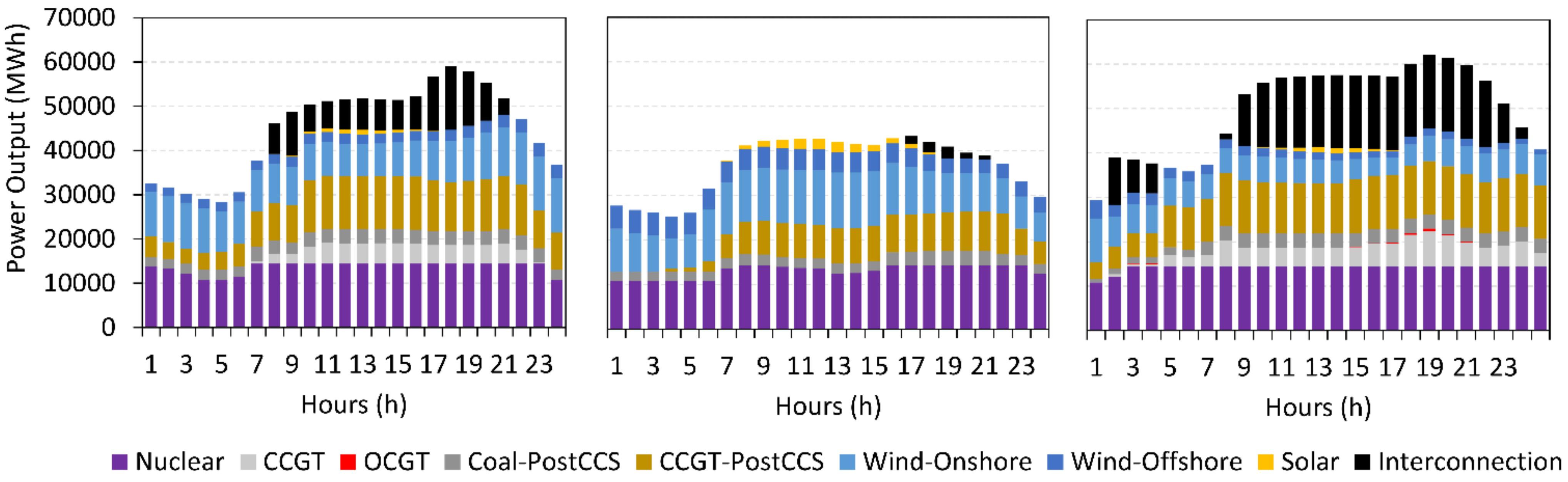




Mac Dowell, N. & Staffell, I. (2016). International Journal of Greenhouse Gas Control, 48, Part 2 (Flexible operation of carbon capture plants), 327–344.
Mac Dowell, N. & Shah, N. (2015). Computers & Chemical Engineering, 74, 169–183.

Power-CCS: Load following, start-up and shut down

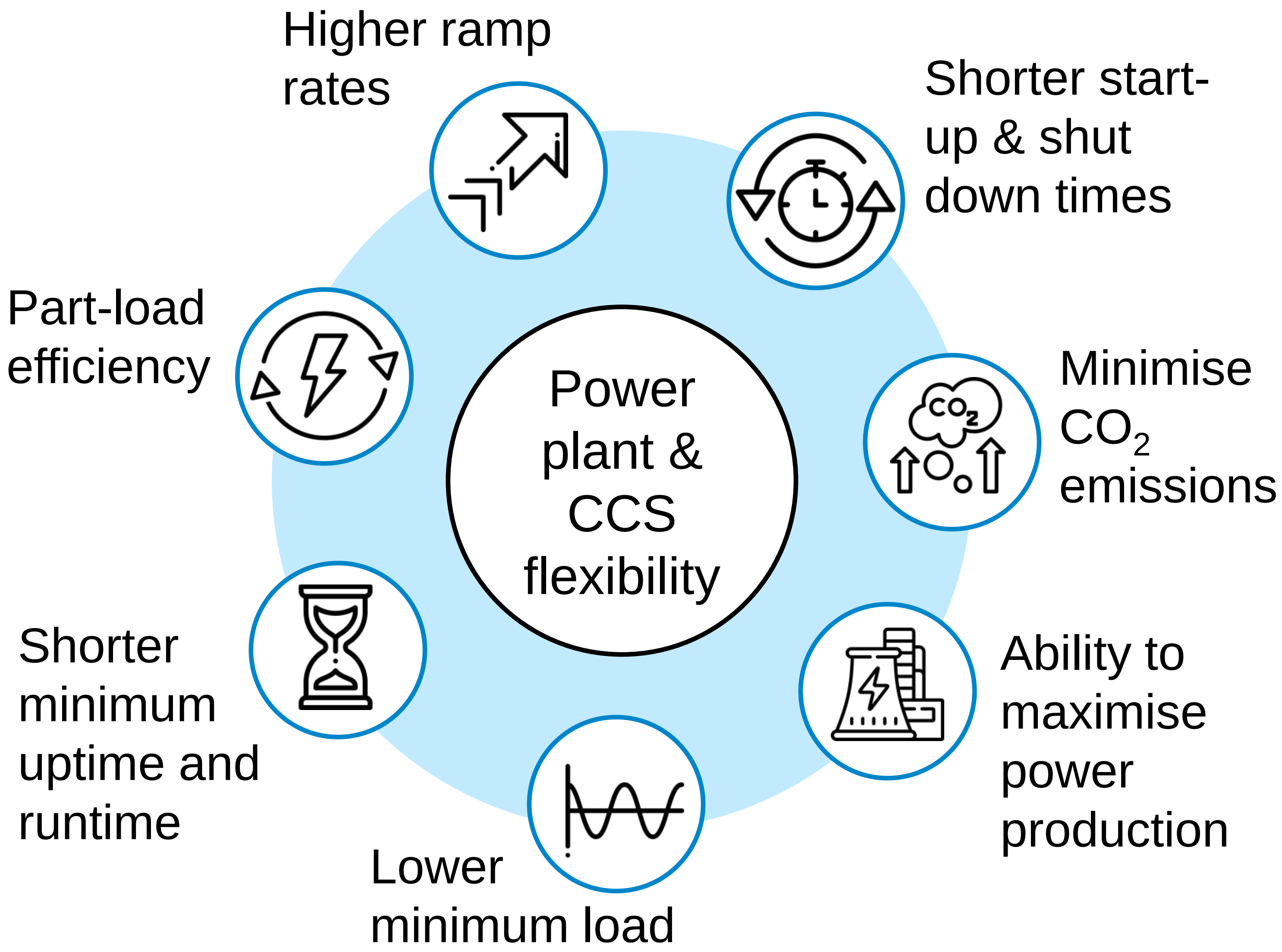
Hourly power generation for three sample days in a 2035 power system scenario



Technology features	NGCC-CCS	Nuclear	Onshore wind
Investment cost	−	−−	++
Operational cost (fuel, O&M)	−	++	++
Firm capacity/reserve services	++	++	−−
Dispatchability/load-following	++	+	−−
Short-term ancillary services	++	++	−−
Operational carbon intensity	++	++	++
Practicality of new project	−	−−	+
System integration	+	++	−

Bui, M. & Mac Dowell, N., editors, (2020). Carbon Capture and Storage, Royal Society of Chemistry, UK. https://doi.org/10.1039/9781788012744.

Flexibility of power plants with CCS



Dispatchable low carbon electricity to the grid

Greater system flexibility

Improve the economic performance of the system

Ensure CO_2 emissions reduction requirements are met

Pilot & demonstration studies of flexible operation

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"Flexible operation" of CCS was proposed for grid support (Gibbins & Crane, 2004)	**Esbjerg pilot plant in Denmark** Coal FG	**CSIRO pilot plant in Australia** Coal FG	**Brindisi demonstration plant in Italy** Coal FG	**TCM demonstration plant in Norway** Natural gas FG	**Sulzer pilot plant in Switzerland** Synthetic NG	**UKCCSRC PACT pilot plant in UK** Synthetic coal	**TCM demonstration plant in Norway** Natural gas FG 80 t_{CO2}/day Step-changes Variable ramp rate ...ne-varying ...ent regen (...et al., 2020)

2004

Developing understanding of flexible operation

1) Process modelling – needs to be validated with plant data.

2) Develop methodology to acquire reliable dynamic pilot plant data for model development.

3) Gaining experience in dynamic/flexible operation at various test facilities.

4) Scaling up: Demonstration scale test campaign, identifying flexibility limits and providing data for model validation.

Year of test campaign

- Dynamic process data unavailable
- Dynamic process data published

We have gained valuable operating experience at dynamic conditions.

Dynamic operating data for model development is being made available.

Gibbins, J. R. & Crane, R. I. (2004). *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy,* 218 (4), 231–239.

Flexible operation of CO_2 capture plants at different scales

Pilot-scale: 0.5 tCO_2/day

Pilot-scale: 1 tCO_2/day

https://www.gasmet.com/wp-content/uploads/2014/10/ukccsrc_pact_carbon_capture_plant.jpg

Demo-scale: 80–275 tCO_2/day

Source: Business Wire/Helge Hanse https://www.process-worldwide.com/index.cfm?pid=9890&pk=763551&fk=0&type=article#1

Bui, M., et al. (2016). International Journal of Greenhouse Gas Control, 48, Part 2 (Flexible operation of carbon capture plants), 188–203.

Tait, P., *et al*. (2018). International Journal of Greenhouse Gas Control, 71, 253–277.
Bui, M., *et al.* (2018). International Journal of Greenhouse Gas Control, 79, 134–153.

Absorption-based CO_2 capture

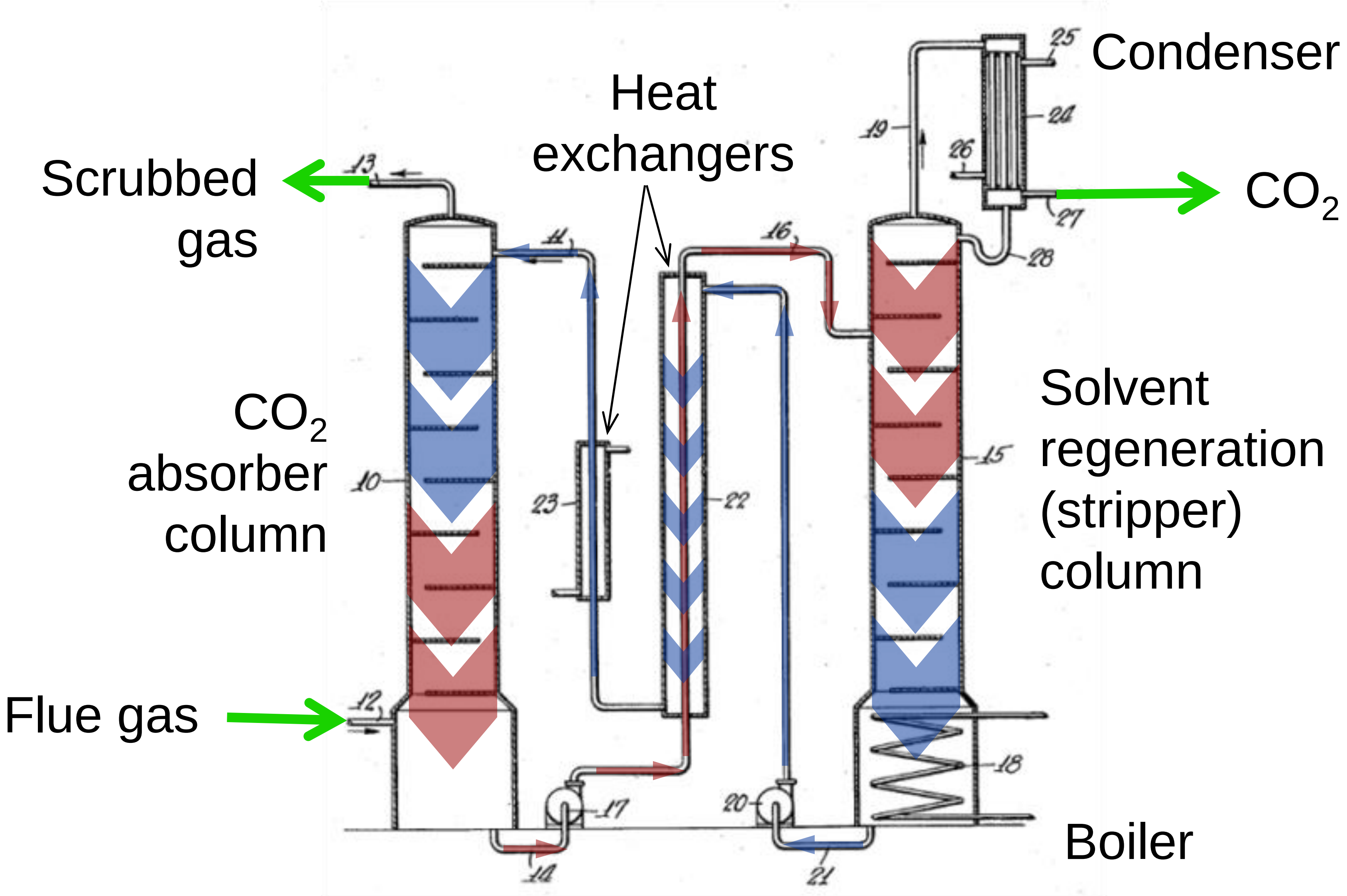

Figure: Bottoms, R. (1930). US Patent No. 1783901.

Flexible operation of a demonstration-scale CO_2 capture plant

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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

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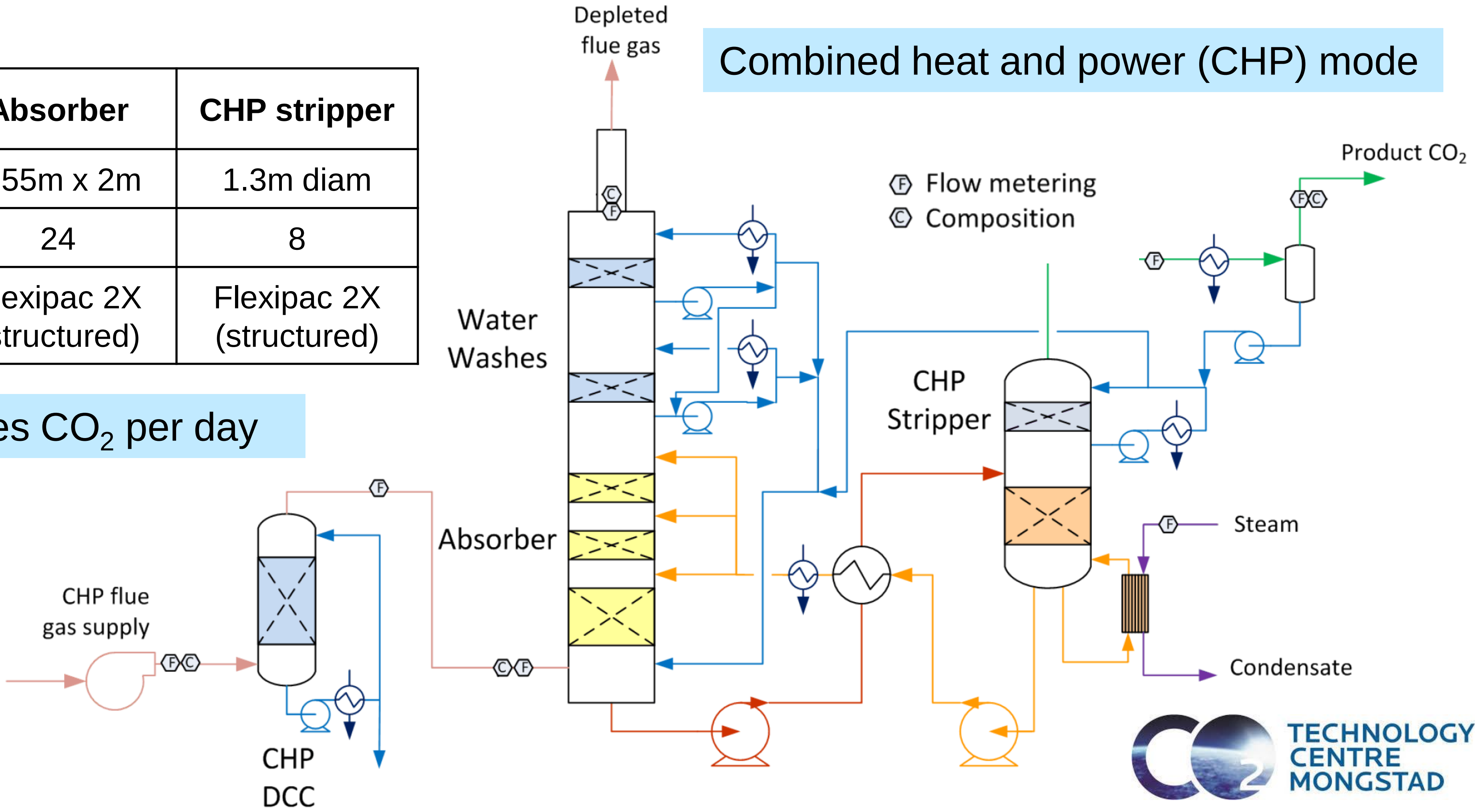
	Absorber	CHP stripper
Cross section dimensions	3.55m x 2m	1.3m diam
Packing height (m)	24	8
Packing type	Flexipac 2X (structured)	Flexipac 2X (structured)

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%

30 wt% MEA

Flexible operation of the TCM CO_2 capture plant

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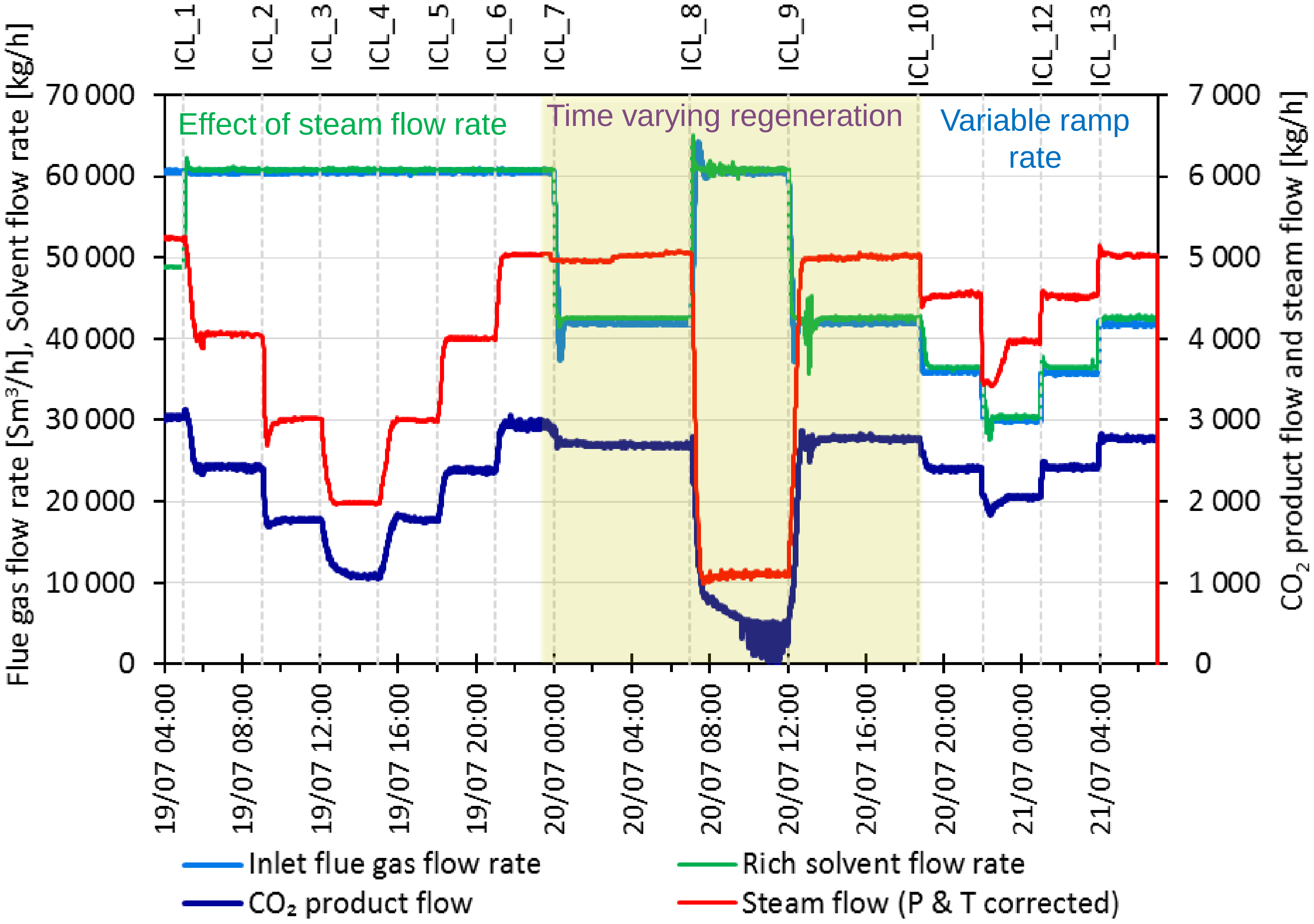
The dynamic operation scenarios of this test campaign are:

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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Time-varying solvent regeneration

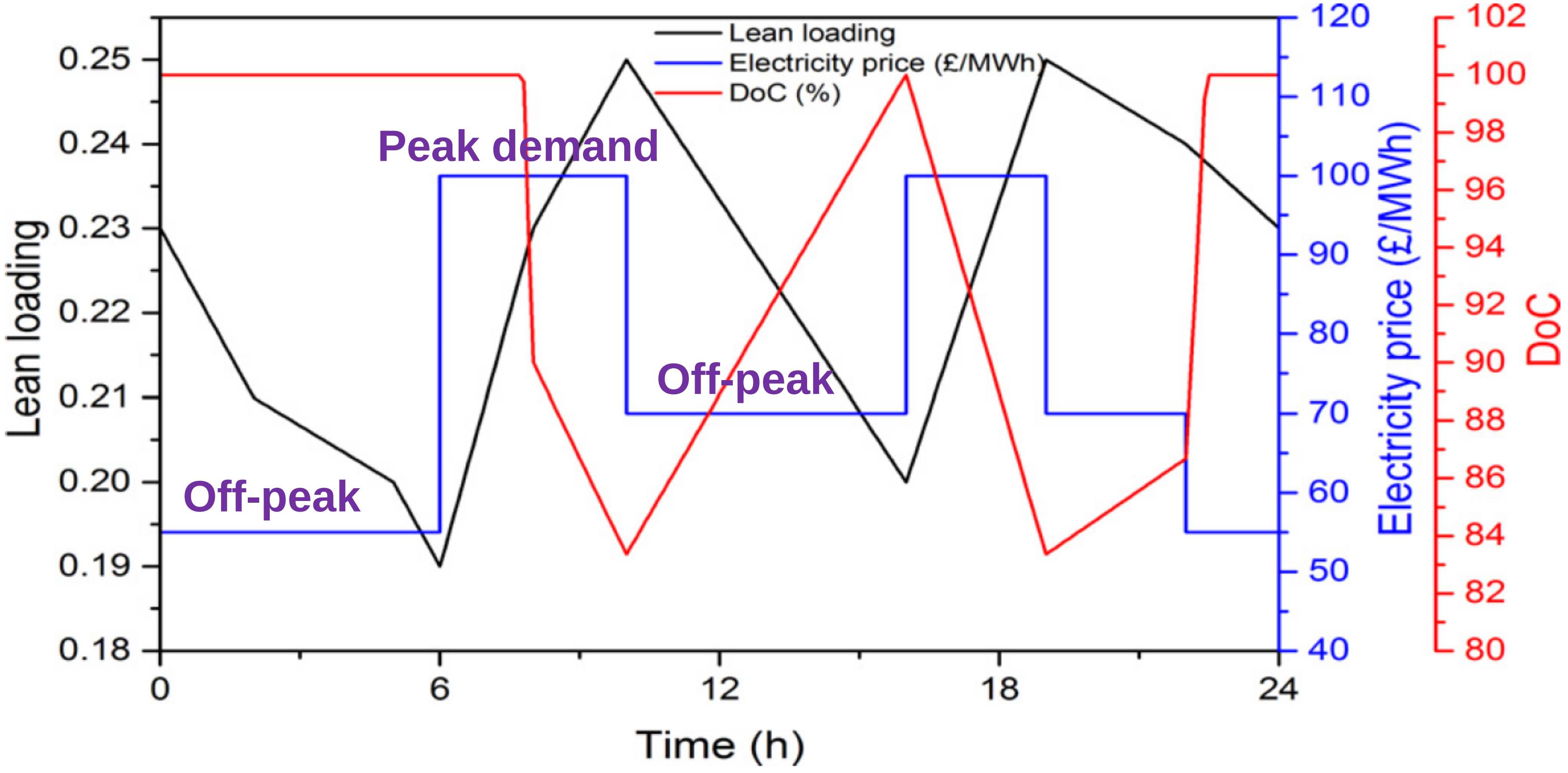
The use of solvent storage tanks involves high capital cost.

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

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

Potentially more cost effective and profitable.

Combined cycle gas turbine power plant



References: Mechleri, E., Fennell, P. S. & Dowell, N. M. (2017). International Journal of Greenhouse Gas Control, 59, 24–39.
Mac Dowell, N. & Shah, N. (2015). Computers & Chemical Engineering, 74, 169–183.

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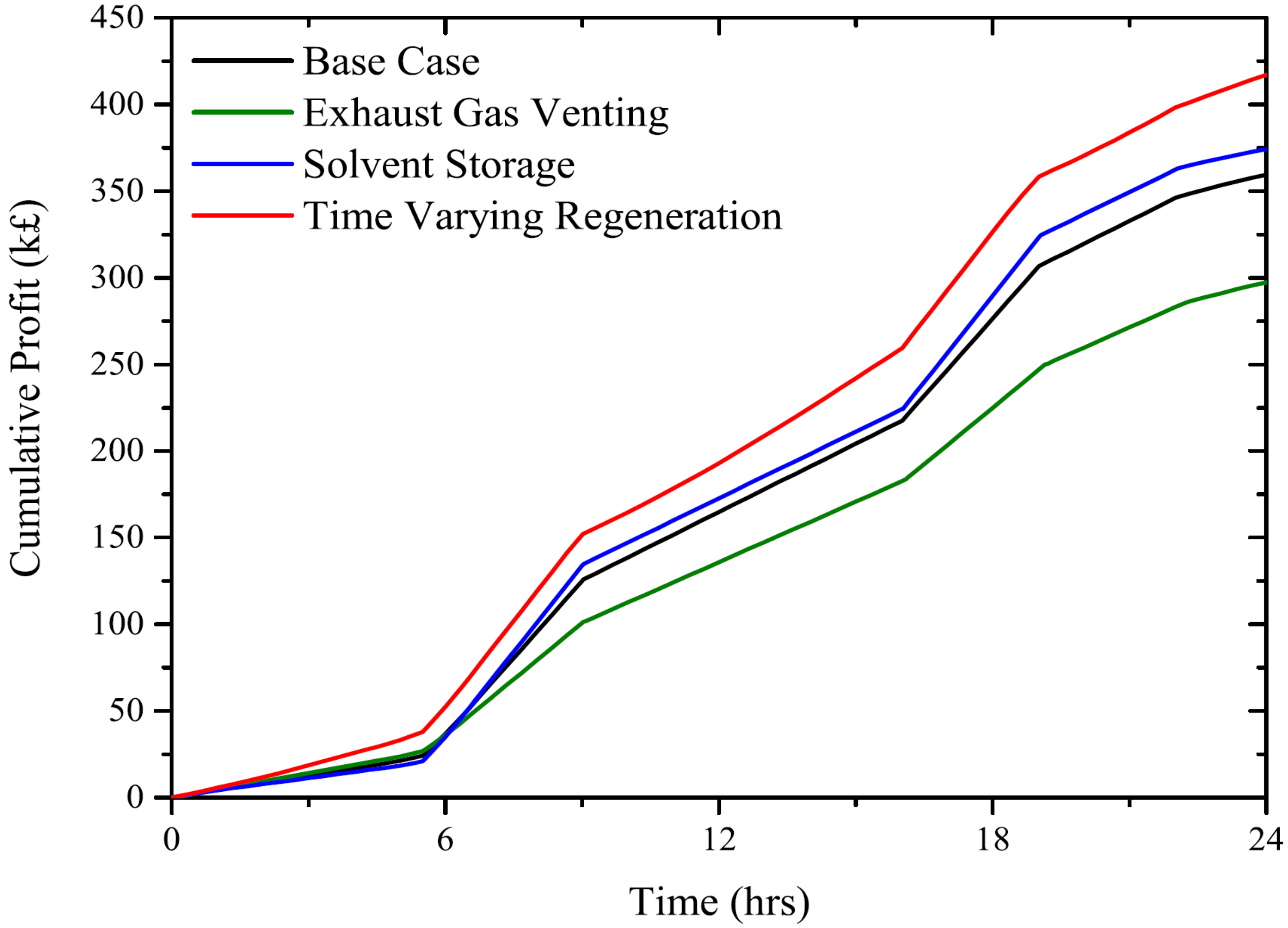
Time-varying solvent regeneration

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

Can we actually do it?



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

Time-varying solvent regeneration

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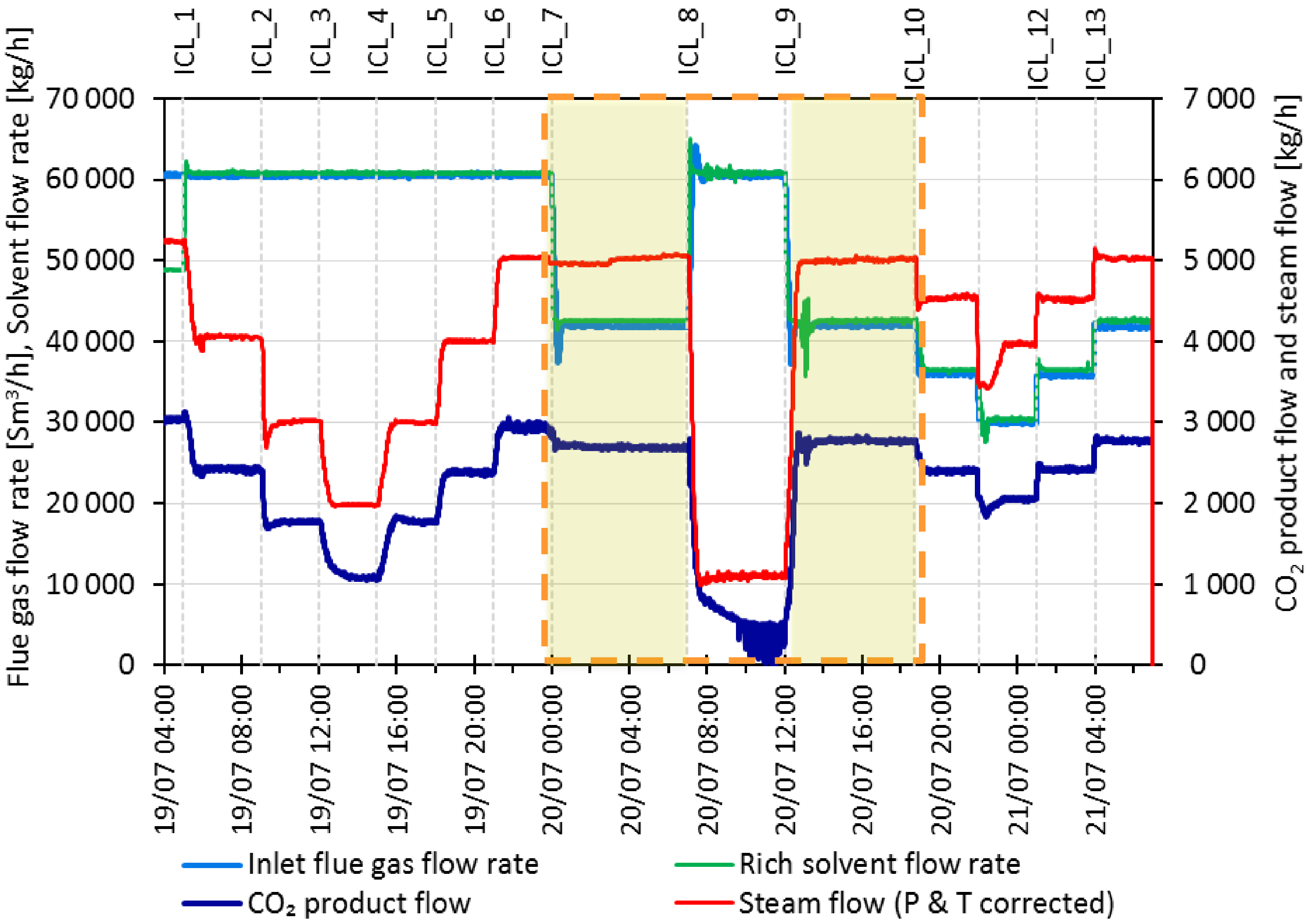
Off-peak electricity prices: Solvent is regenerated, reducing power output → expect lower flue gas flow rates.

Increase steam flow to reboiler:

- Decreases lean CO_2 loading
- Increases degree of capture

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}



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Time-varying solvent regeneration

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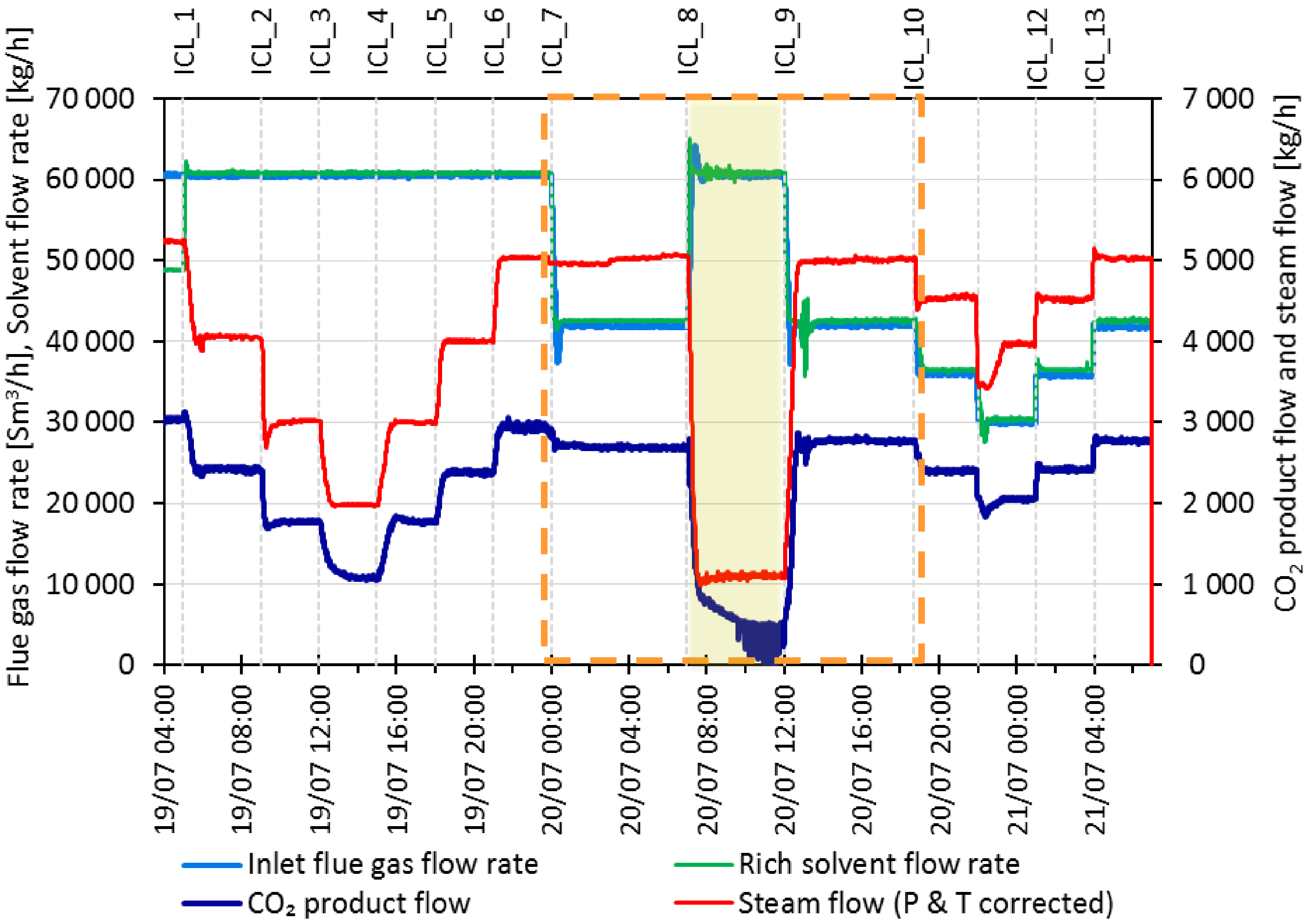
Peak electricity prices: accumulate CO_2 in the amine

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

Reduce steam flow to reboiler:
- Increase in lean CO_2 loading
- Degree of capture reduces



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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}

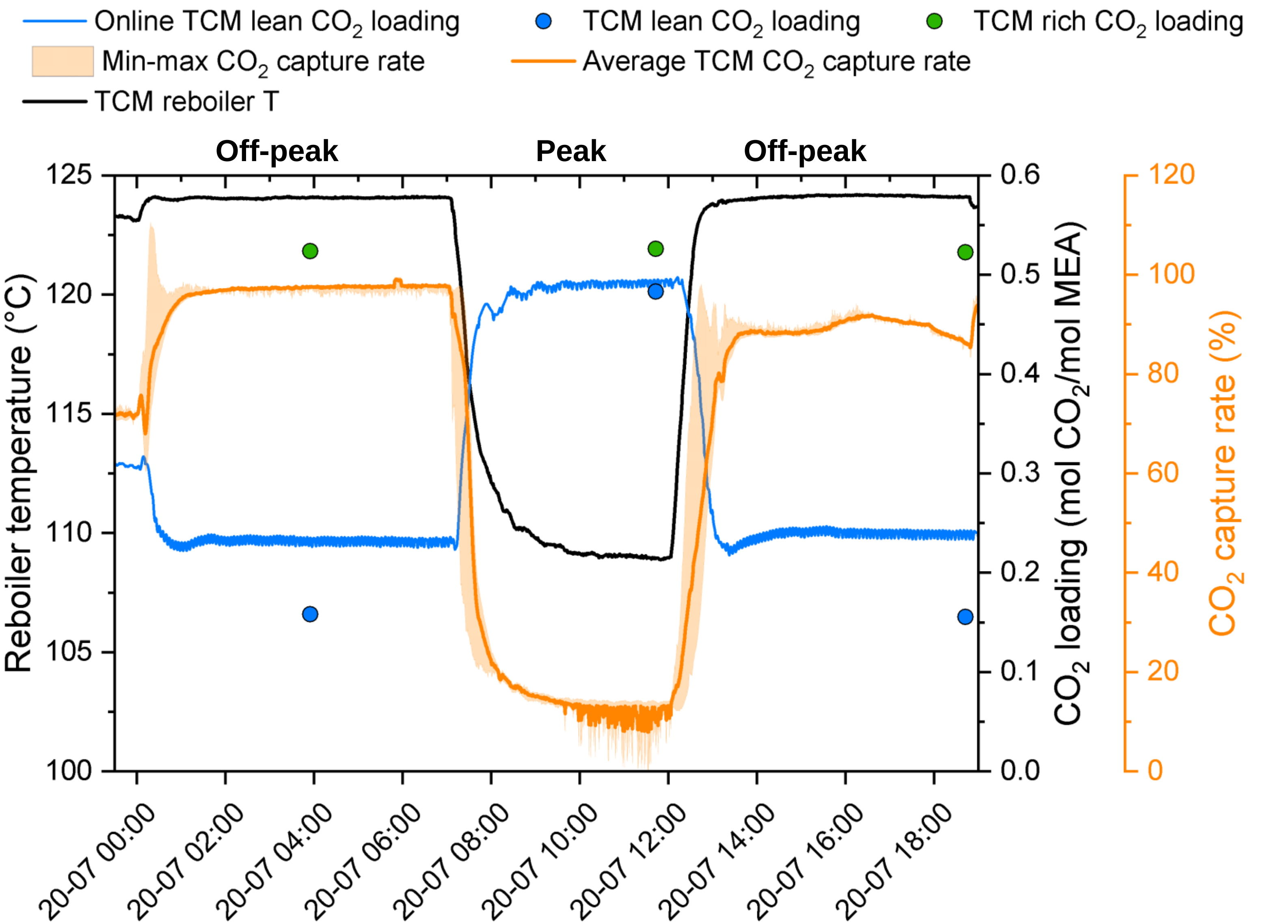
Peak: *CO_2 is "stored" in solvent and lean CO_2 loading increases.*

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

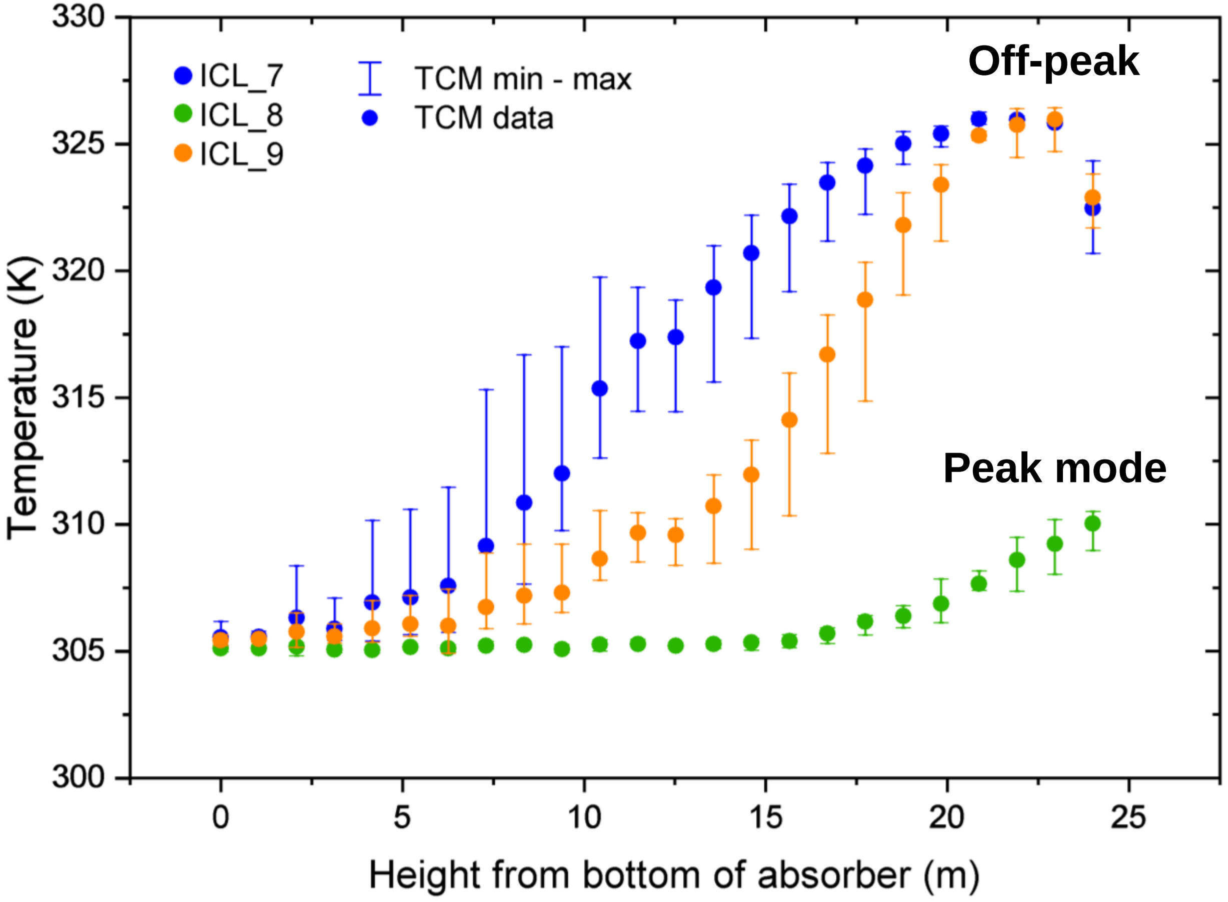
<u>Cumulative</u> CO_2 capture rate: 66.5%

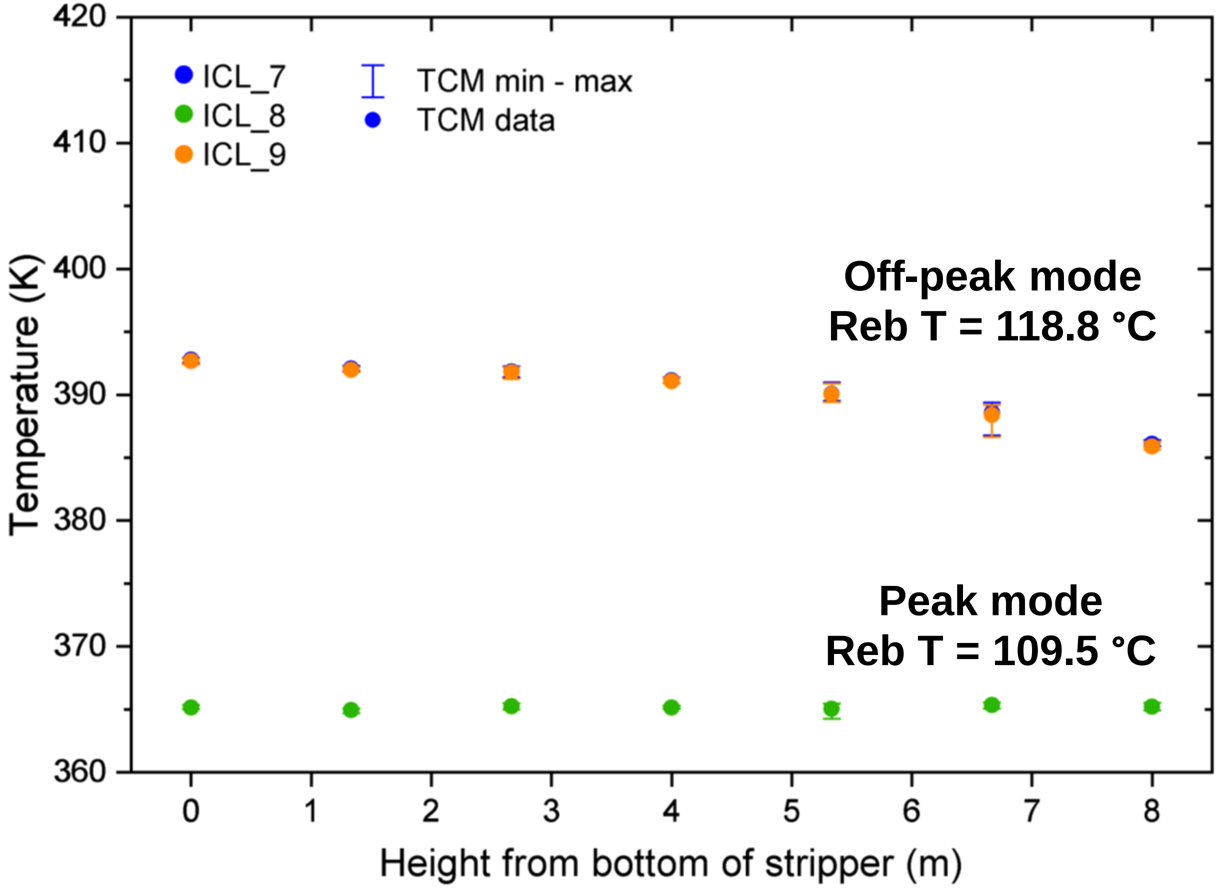


Bui, M., Flø, N. E., de Cazenove, T., Mac Dowell, N., (2020). International Journal of Greenhouse Gas Control, 93, 102879.

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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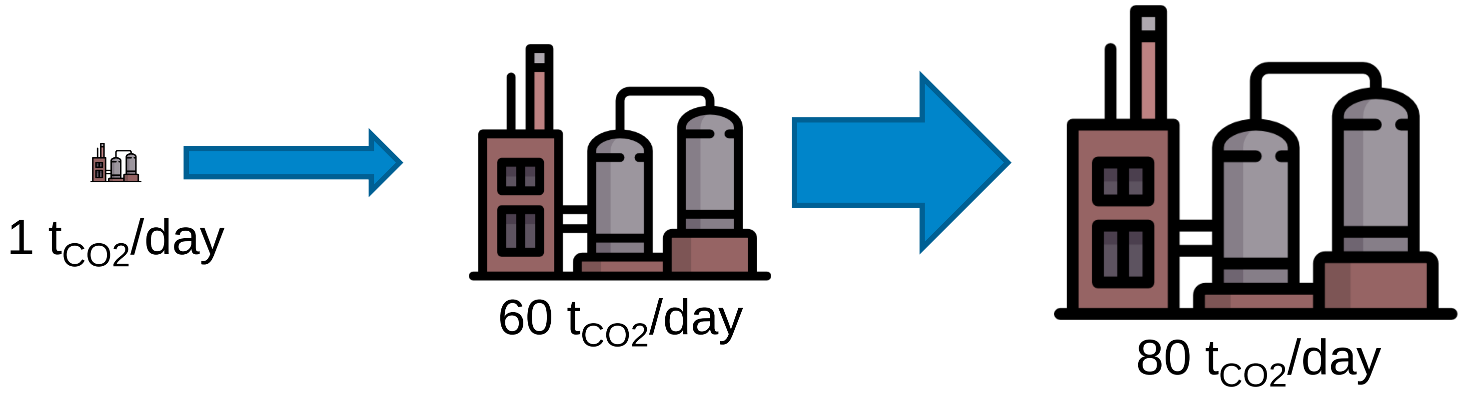
Effect of scale on process dynamics

The flexibility of the capture plant may be limited by the **process control** and is a function of **plant scale**.



	UKCCSRC PACT pilot plant	Brindisi CO_2 capture plant		TCM demonstration plant	
CO_2 capture capacity	1 t_{CO2}/day	60 t_{CO2}/day		80 – 200 t_{CO2}/day	
Volume solvent inventory	0.470 m^3	61 m^3		38.2 – 40.8 m^3	
Solvent circulation time	36 min	105 min	146 min	41 min	71 min
→ corresponding solvent flow	1 m^3/h	35 m^3/h	25 m^3/h	58 m^3/h	34 m^3/h

Data from: Tait, P., et al. (2018). *International Journal of Greenhouse Gas Control,* 71**,** 253–277.
Bui, M., et al. (2018). *International Journal of Greenhouse Gas Control*, 79, 134–153.

Data from: Montañés, R. M., et al. (2018). International Journal of Greenhouse Gas Control, 73, 42–59.
Enaasen, N., et al. (2014). *Energy Procedia,* 63**,** 1040-1054.

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Start-up & shut down of power-CCS systems

Rise in the frequency of start-up & shut down (SUSD) cycles is expected with higher iRES.

If CO_2 emissions increase considerably, this would undermine the value proposition of CCS as a flexible, low carbon asset.

Objectives:

- Identify measures that can reduce/minimise CO_2 emissions and duration time of SUSD.
- Use a combination of dynamic modelling with plant test results (e.g., TCM, Boundary Dam, UKCCSRC PACT plant).

SUSD Test Campaign at TCM with Cesar-1: 27 wt% AMP+ 13 wt% PZ

TCM CO_2 capture facility, Mongstad Norway

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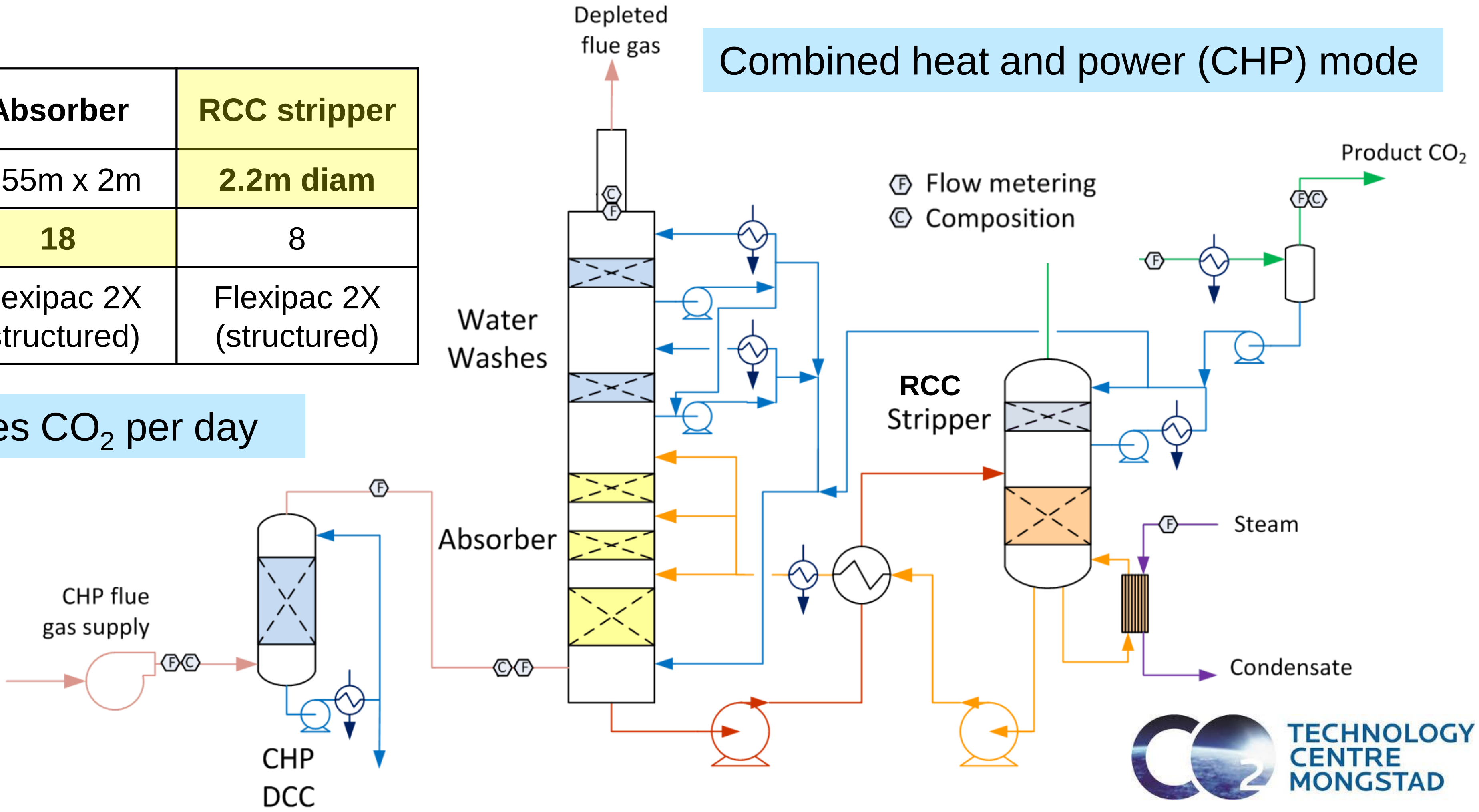
	Absorber	RCC stripper
Cross section dimensions	3.55m x 2m	**2.2m diam**
Packing height (m)	**18**	8
Packing type	Flexipac 2X (structured)	Flexipac 2X (structured)

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

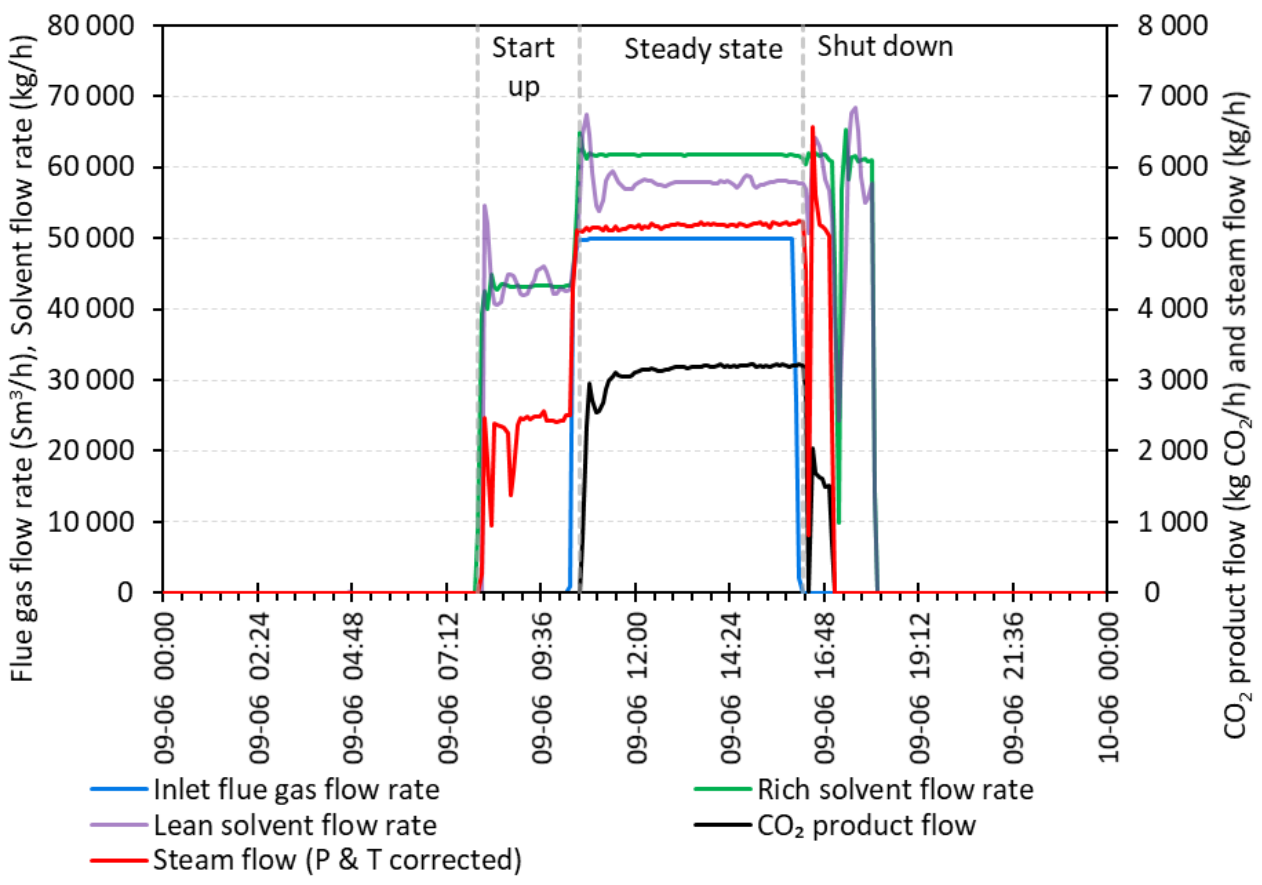


Refinery catalytic cracker (RCC) mode captures 200 t_{CO2}/day, gas CO_2 content 12.9 mol%

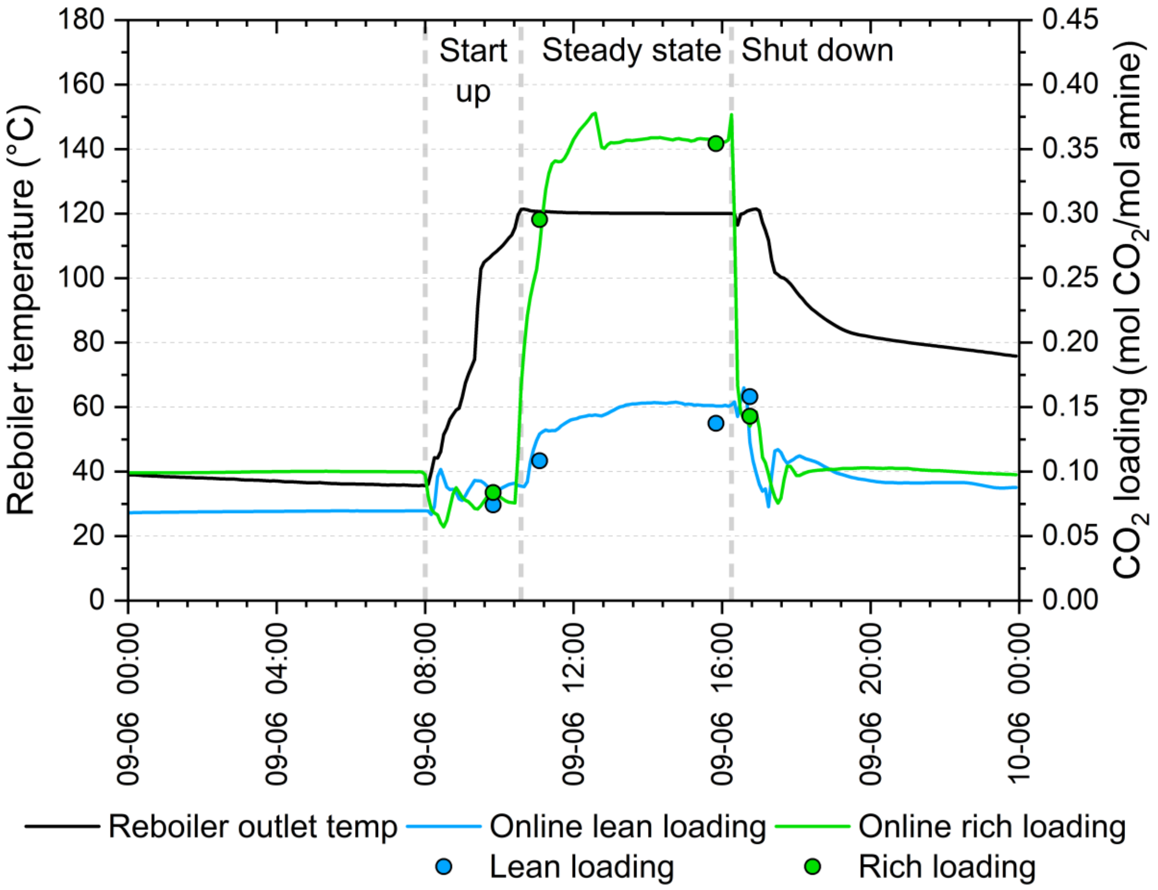
Cesar-1: 27 wt% AMP+ 13 wt% PZ

Cold start-up and normal shut down

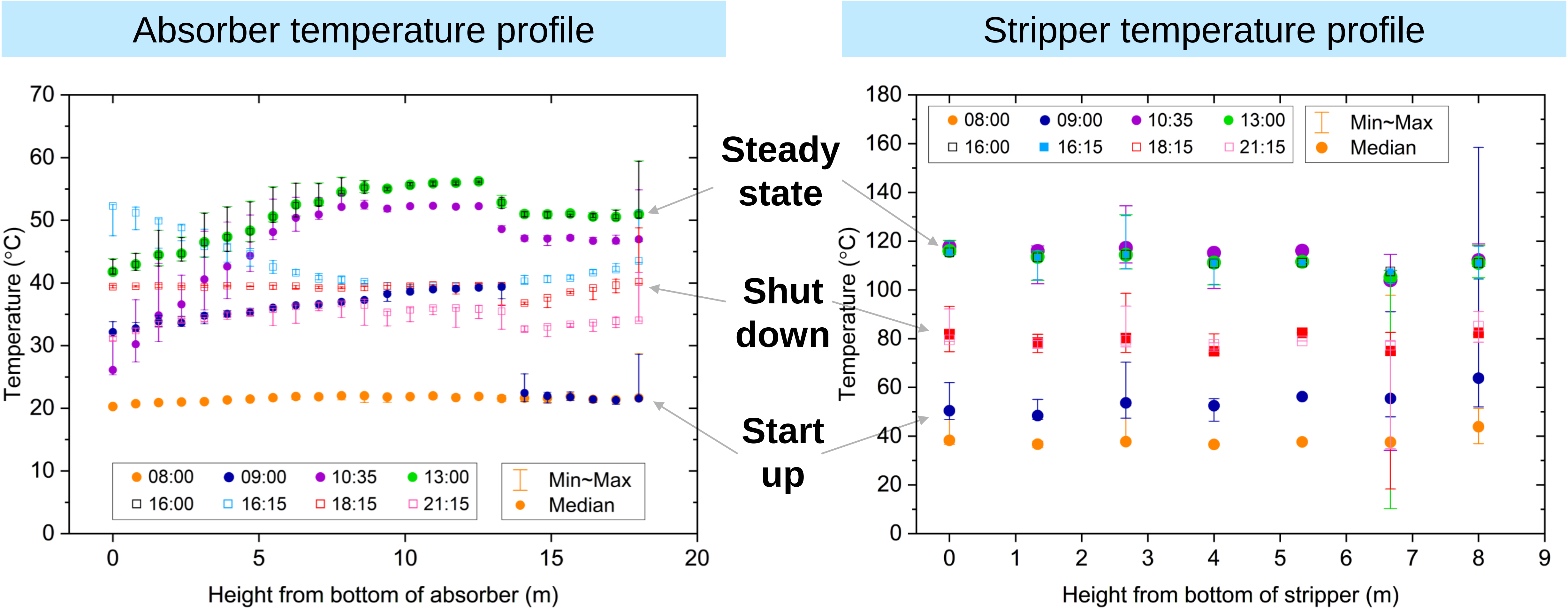
Changes in key process parameters



Reboiler temp & CO_2 loading



Column temp during cold start-up & normal shut down



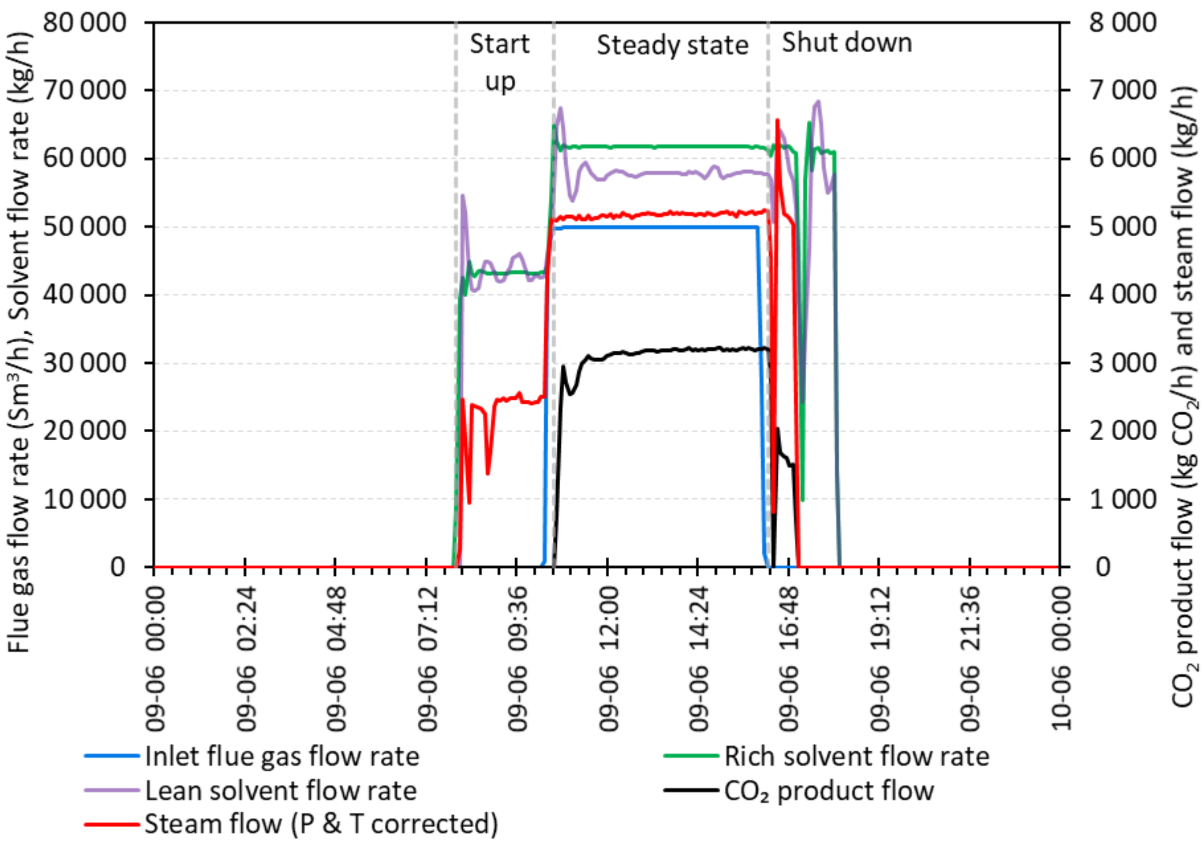
○ = Start-up, temp increasing   □ = Shut down, temp decreasing

10:35 flue gas fed into absorber

Cold vs Hot: Major difference in start-up time

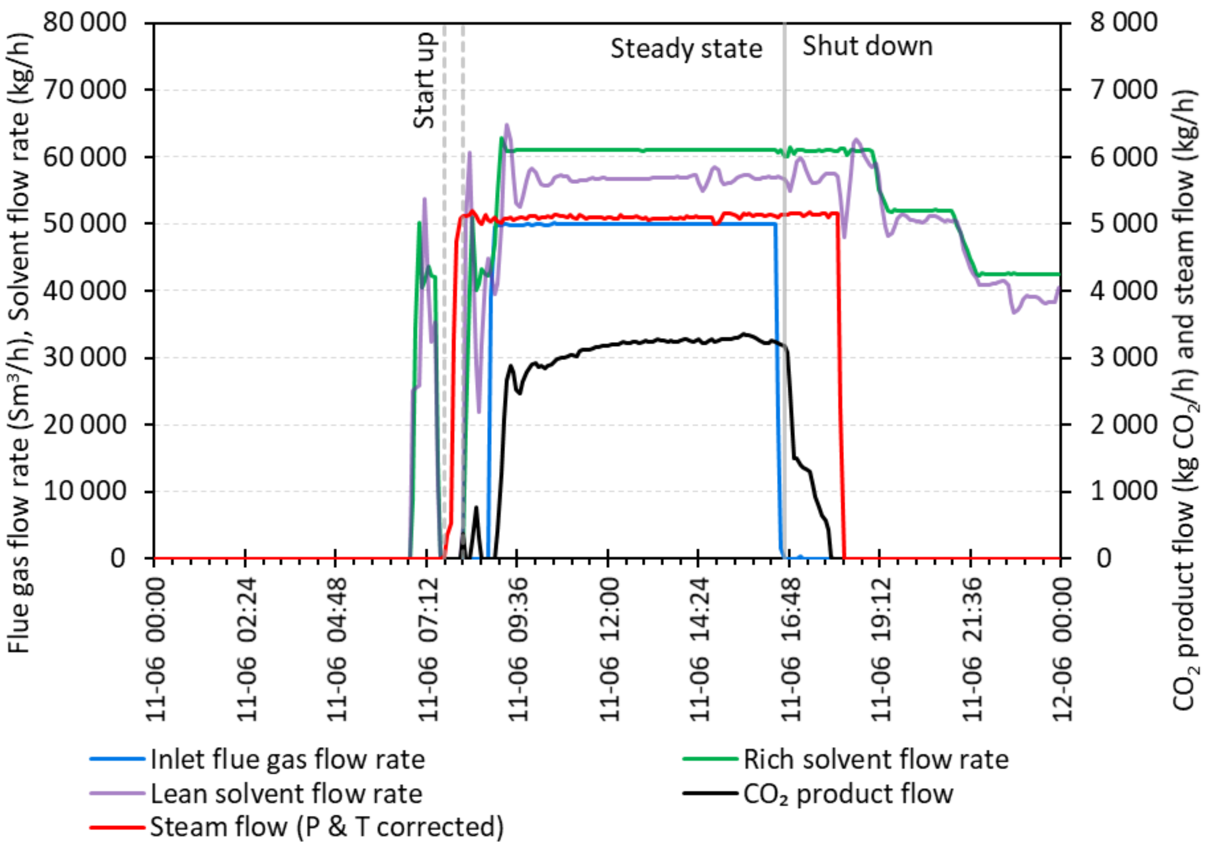
Testing at TCM with Cesar-1: 27 wt% AMP+ 13 wt% PZ

Cold start-up



Start-up time = 2 h 35 min

“Improved” hot start-up



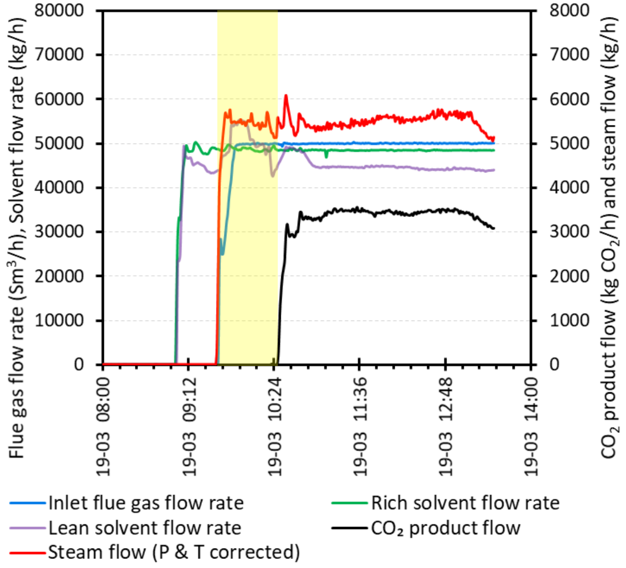
Start-up time = 30 min

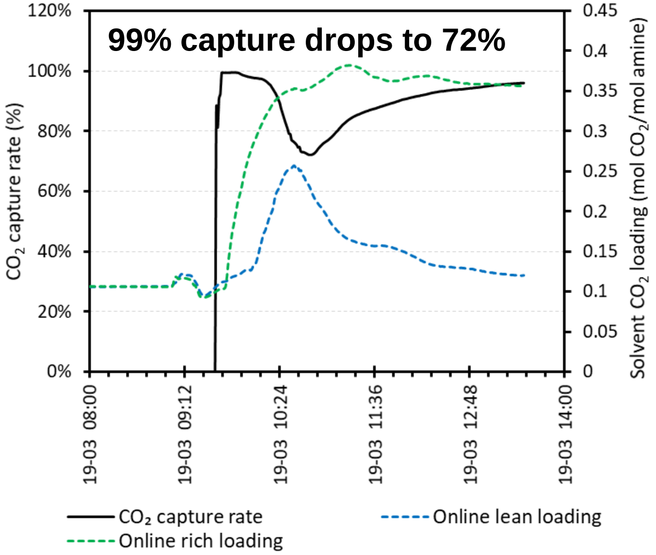
Start-up time = time to reach target steam flow rate

Conventional hot start-up = 1 h 55 min

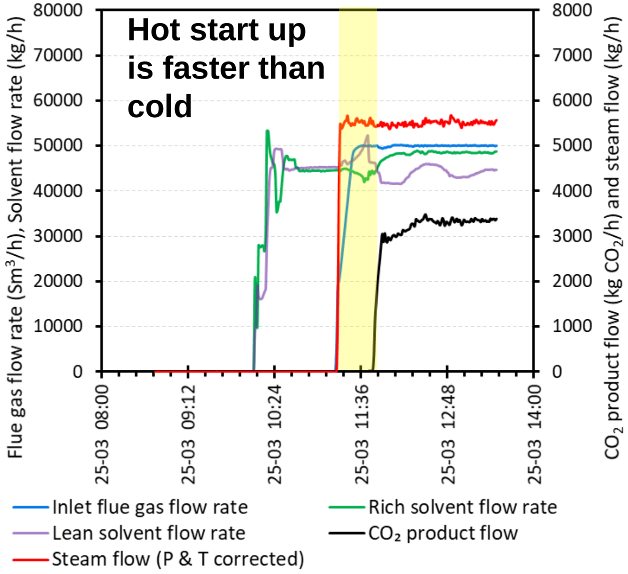
CCS start-up & shut down

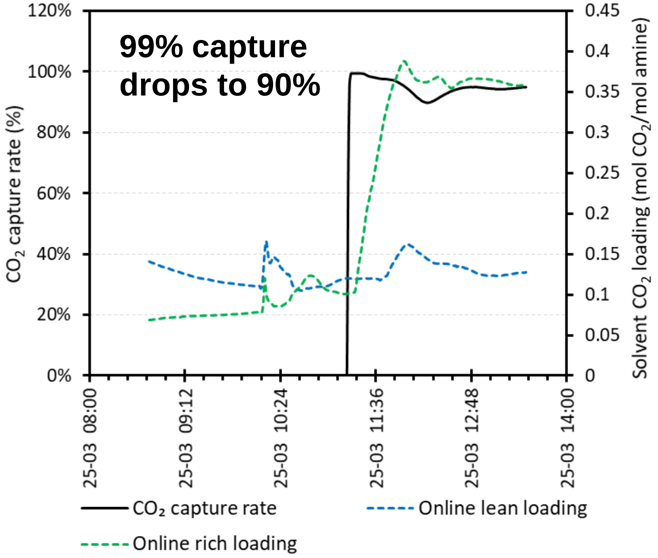
Cold start-up





Hot start-up





Cold start-ups take longer and have higher CO_2 emissions compared to hot start-ups.

Steam availability – the earlier steam is available, the lower the CO_2 emissions.

Start-up with lower lean loading can provide higher capture rates of 99% initially.

Different solvent inventories 40 m^3 vs 50 m^3:

- Shut down is faster with a smaller inventory, leaning out a smaller volume
- Start-up benefits from larger inventory as the plant can sustain higher CO_2 capture rates for a longer during heating of plant.

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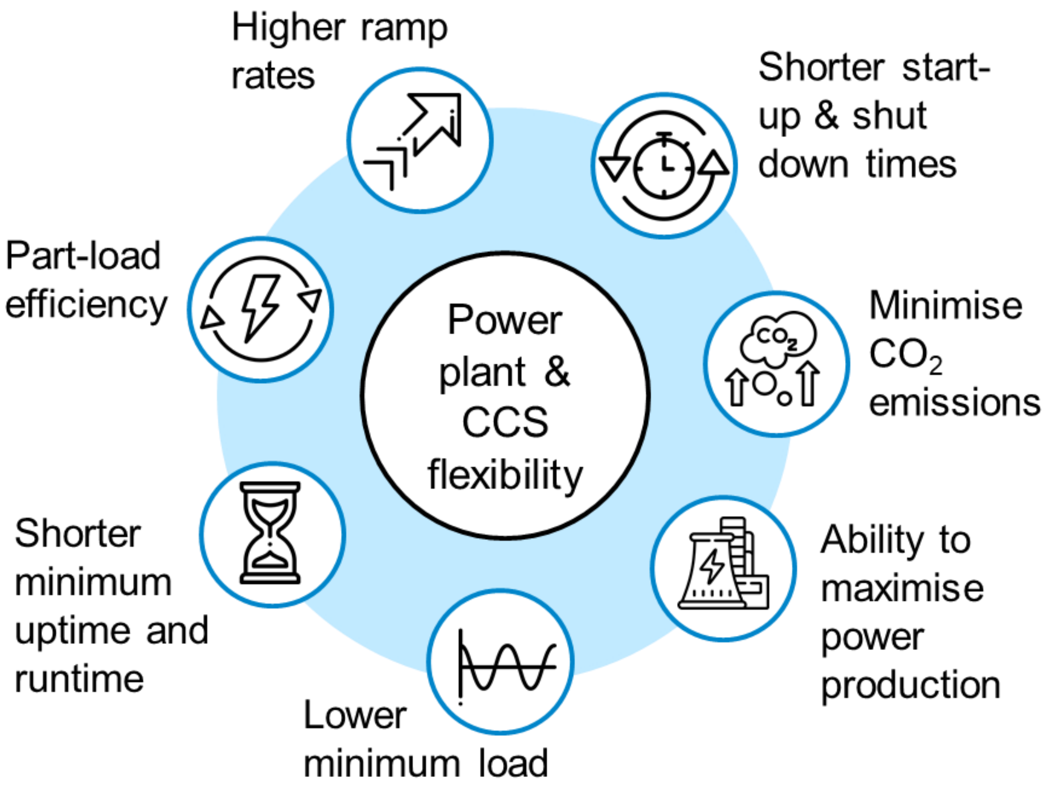
Flexible operation of CO_2 capture plants



With more intermittent renewables in energy systems, power plants with CCS need to be highly flexible.

Pilot- or demonstration-scale studies of novel operation strategies provide certainty around technical feasibility.

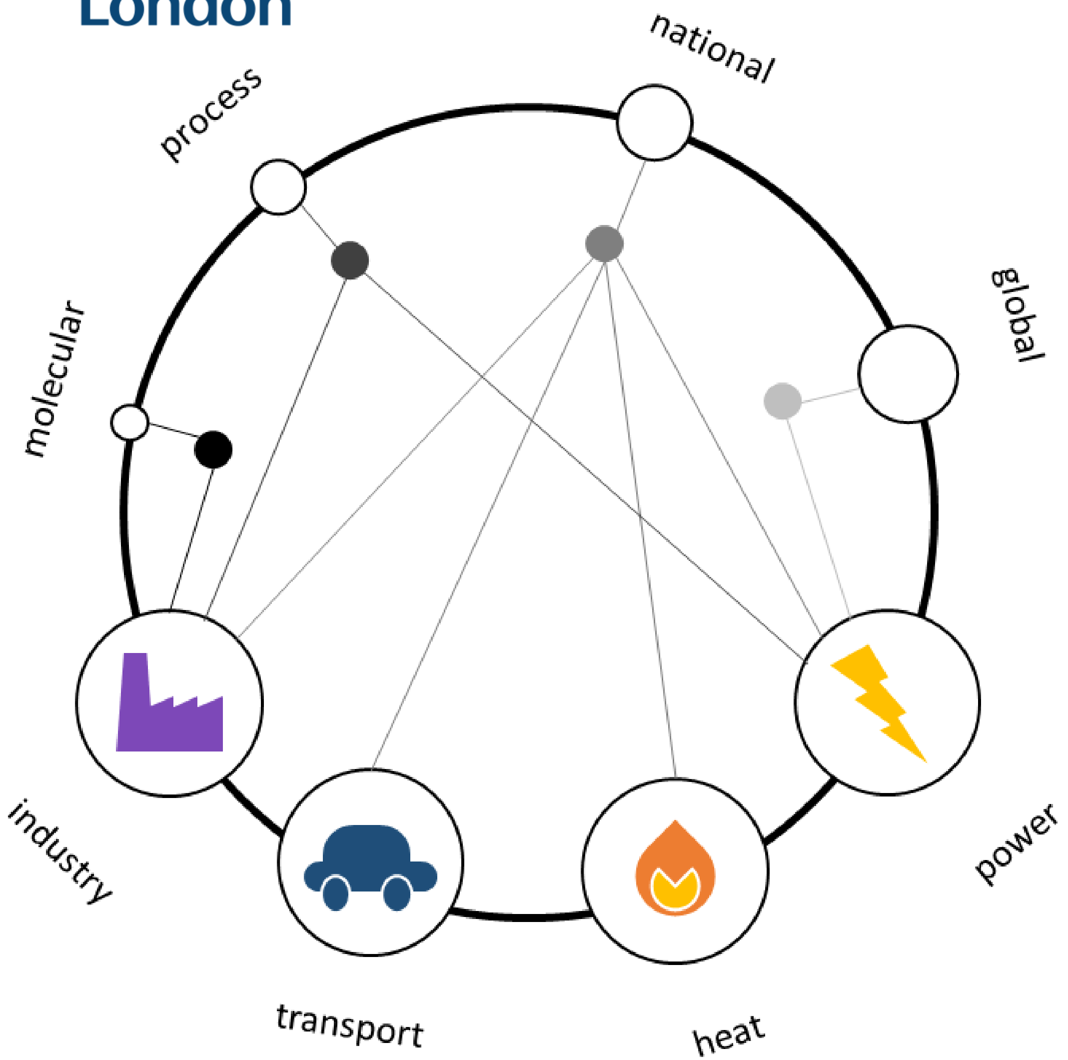
Pilot plant studies have demonstrated flexible operation in processes using MEA at different plant scales (pilot to demonstration scale). What about other solvent types?

To development robust dynamic process models:

- Availability of dynamic plant data is top priority,
- Ensure experimental methods provide reliable data.

Experimental R&D will help identify how to maximise flexibility through design/operation and optimised process control, especially during highly transient conditions, e.g., start-up, shut down.

Role & value of carbon capture & storage



The technical elements of CCS are well-understood and the financial/commercial models are becoming increasingly clear.

Large-scale deployment CCS is needed for deep decarbonisation. There is substantial evidence of the economy-wide GDP and employment benefits associated with CCS deployment.

CCS to provide dispatchable, low-carbon power to balance the increased intermittent renewables.

CCS will also have important roles in greenhouse gas removal (GGR), hydrogen production and industrial decarbonisation.

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Extra slides

Power plants are relatively flexible

Type of point		Start-up time*	Start-up cost (USD/MW instant start)	Minimum load [% Pnom]	Efficiency (at 100% load)	Efficiency (at 50% load)	Avg. ramp rate [% Pnom/min]	Minimum uptime	Minimum downtime
Hard coal	Average plant	2–10 h[a]	> 100	25–40%[a]	43%	40%	1.5–4%[a]	48 h	48 h
	Post flexibilisation	80 min–6 h[a]	> 100	10–20%[b]	43%	40%	3–6%[a]	8 h	8 h
Lignite	Average plant	4–10 h[a]	> 100	50–60%[a]	40%	35%	1–2%[a]	48 h	48 h
	Post flexibilisation	75 min–8 h[c]	> 100	10–40%[b]	40%	35%	2–6%[c]	8 h	8 h
CCGT	Average plant	1–4 h[a]	55	40–50%[a]	52–57%	47–51%	2–4%[a]	4 h	2 h
	Post flexibilisation initiatives	30 min–3 h[a]	55	20–40%[c]	52–57%	47–51%	8–11%[c]	4 h	2 h
OCGT	Average plant	5–11 min	< 1–70	40–50%	35–39%	27–32%	8–12%	10–30 min	30–60 min
	Post flexibilisation/ advanced plant	5–10 min	< 1–70	20–50%	35–39%	27–32%	8–15%	10–30 min	30–60 min
ICE[c]	Average plant	5 min	< 1	20% (per unit)	45–47%	45–47%	> 100%	< 1 min	5 min
	Post flexibilisation/ advanced plant	2 min	< 1	10% (per unit)	45–47%	45–47%	> 100%	< 1 min	5 min

* Start-up times are longer for cold start-up (plant shut for more than 48 hours) than for hot start-up (plant shut for less than 8 hours).

Notes: h = hour; min = minute; MW = megawatt; Pnom = nominal power.ICE = Natural gas fired internal combustion engine
Sources: [a]Agora Energiewende (2017); [b]Henderson (2014); [c]Feldmüller (2017); [d]Wärtsilä and Roam Consulting (2018).

Improvement to plant flexibility could provide reduced SUSD times.

Natural gas-fired systems are comparatively more flexible than coal-fired systems in terms of start up time and ramp rates

International Renewable Energy Agency (2019), Innovation Landscape Brief: Flexibility in Conventional Power Plants, Abu Dhabi.

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TCM demonstration of flexible operation

Novel flexible operation strategies shown to be feasible at demonstration scale.

Time-varying solvent regeneration: CO_2 can be “stored” within the amine liquid

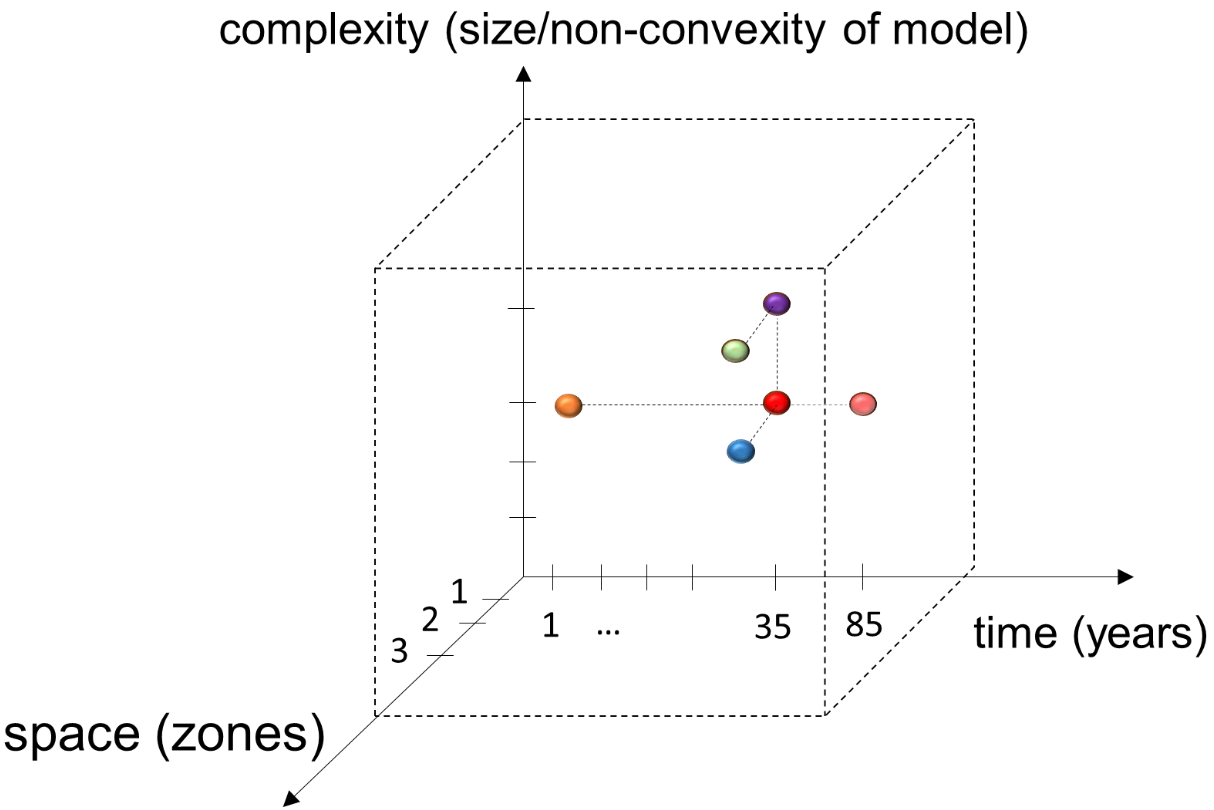
Variable ramp rate: different ramp rates can be applied in succession. By maintaining a constant L/G ratio, CO_2 capture performance (capture % and loading) will remain constant

Start-up and shut down protocols: demonstrated strategies to reduce start up and shut down time and CO_2 emissions.

This dynamic data has been published, making it available for others to use for dynamic model development.

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

Electricity Systems Optimisation Framework



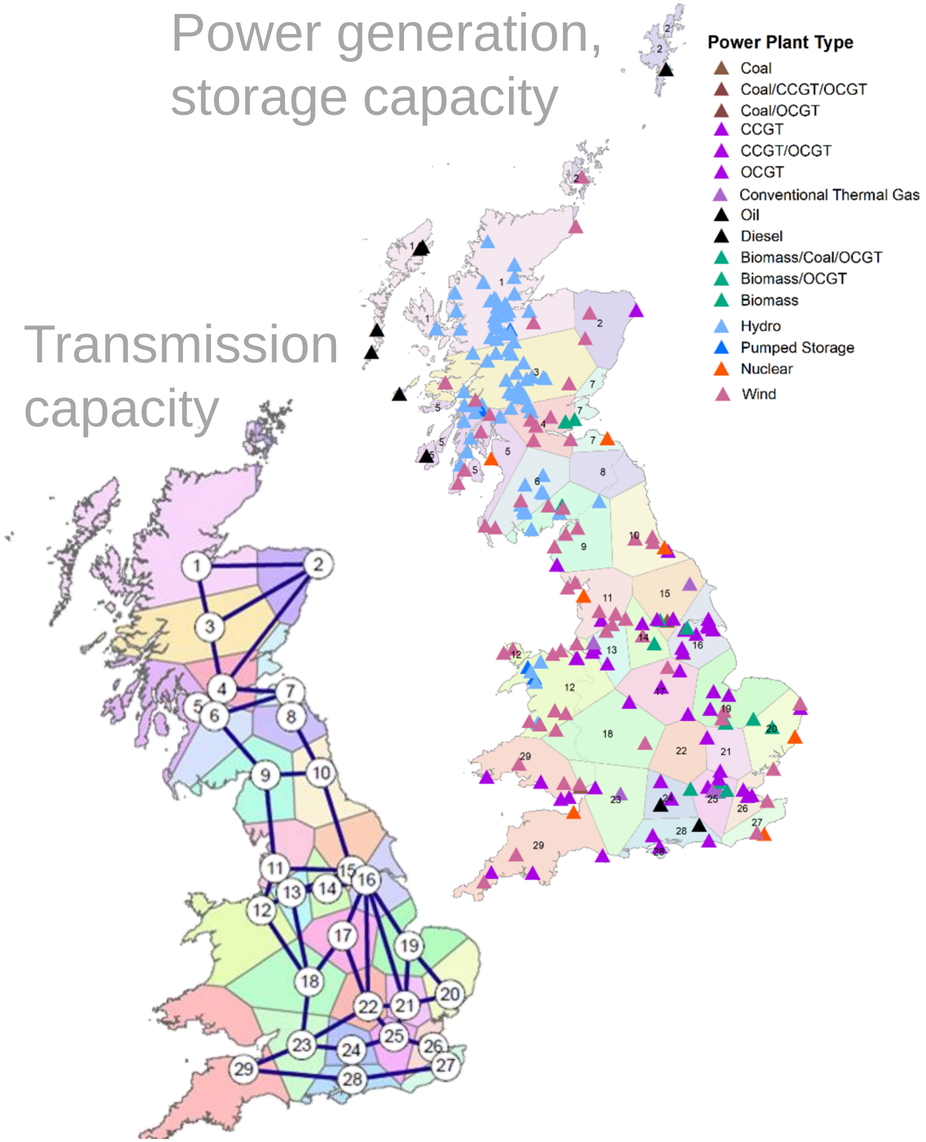
Characteristic		Model Name
1 node, clustered and full hourly, one year		ESO
1 node, full hourly, 35 years		ESO-X
1 node, 35 years, endog. tech. LR		ESO-XEL
multi-zone, clustered time		ESONE-X/-XEL

Available in GAMS, AIMMS, (soon) python/pyomo

Heuberger, C. F., et al. (2016). Energy & Environmental Science, 9 (8), 2497-2510.
Heuberger, C. F. & Mac Dowell, N. (2018). Joule, 2 (3), 367-370.

Open source on GitHub: https://zenodo.org/record/1212298

ESONE Model Formulation



$\forall i \in I$ $\forall a \in A$	**Capacity expansion**	• Initial supply and transmission capacity • Build rate constraints (supply, store, transmiss.) • Life time constraints • Maximum resource constraints
$\forall c \in C$	**System-wide constraints**	• Electricity demand • Reserve requirements • Inertia requirements • Emission target
$\forall z \in Z$	**Transmission**	• Transmission between zones
$\forall t \in T$	**Tech.-wise constraints** **Integer scheduling**	• Power, Reserve, inertia provision • Flexibility of generation/storage units • Carbon emissions by technology • Uptime and downtime
sum	**Objective**	min { CAPEX + mode-specific OPEX }

ESO-X Model Formulation

Characteristic	Model Name
1 node, clustered and full hourly, one year	ESO
1 node, full hourly, 35 years	ESO-X
1 node, 35 years, endog. tech. LR	ESO-XEL
multi-zone, clustered time	ESONE-X/-XEL

$\forall i \in I$ $\forall a \in A$	**Capacity expansion**	• Initial supply capacity • Build rate constraints (supply, store) • Life time constraints • Maximum resource constraints
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