The prospects of flexible natural gas-fired CCGT with CCS within a green taxonomy

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Flexible CCS in future electricity systems

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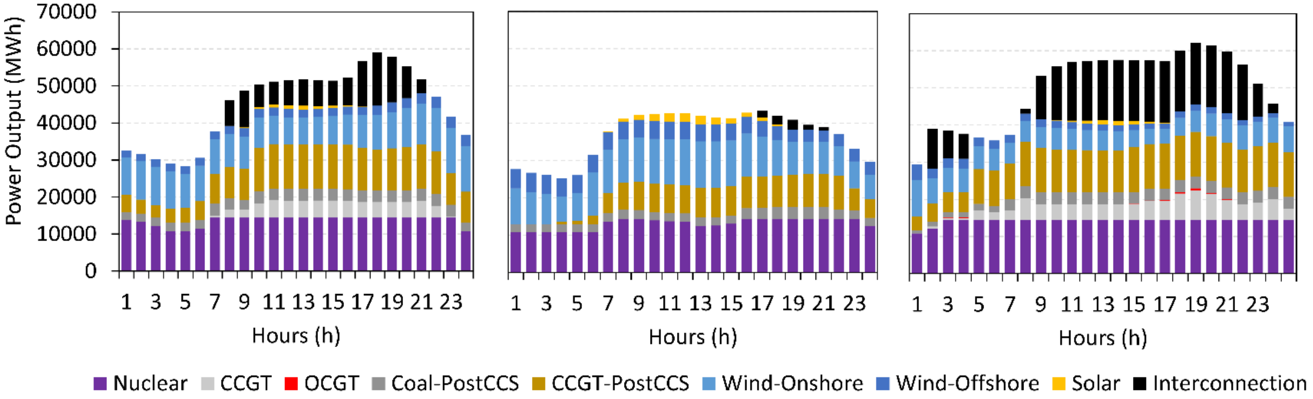
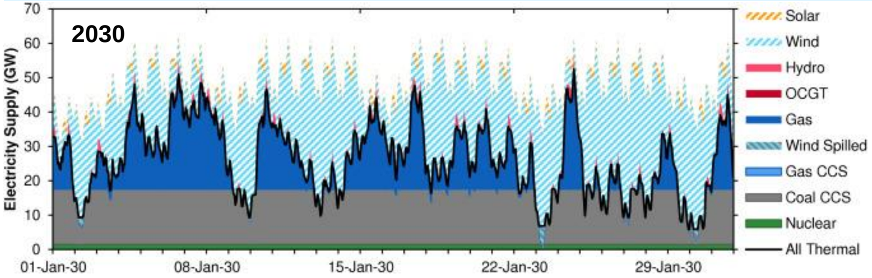
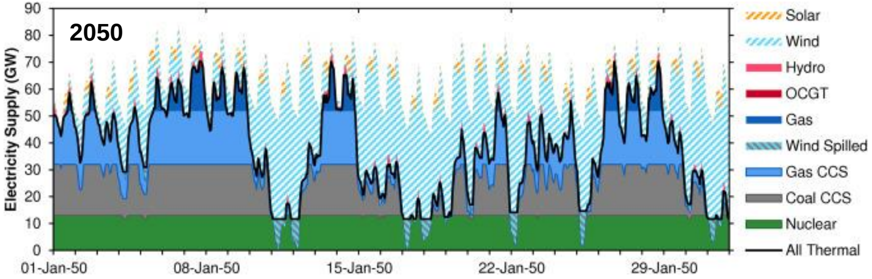
Hourly power generation for three sample days in a 2035 UK power system



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

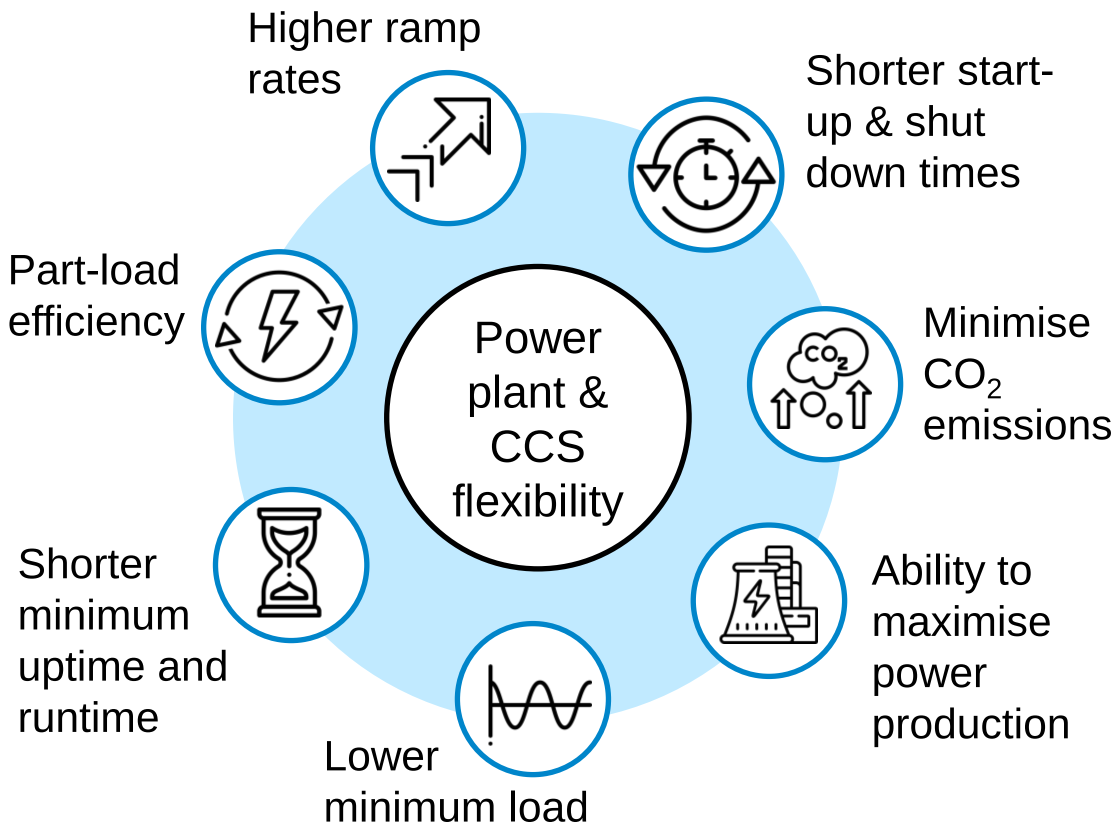
Electricity supply for the UK from 2030 to 2050





Bui, M. & Mac Dowell, N., editors, (2020). Carbon Capture and Storage, Royal Society of Chemistry, UK. https://doi.org/10.1039/9781788012744.
Mac Dowell, N. & Staffell, I. (2016). International Journal of Greenhouse Gas Control, 48, Part 2 (Flexible operation of carbon capture plants), 327–344.

Flexibility of power plants with CCS



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 will undermine the value proposition of CCS.

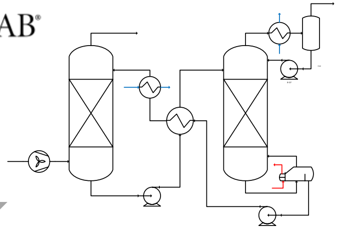
Need to ensure CO_2 emissions reduction requirements are being met.

Technology development & delivery

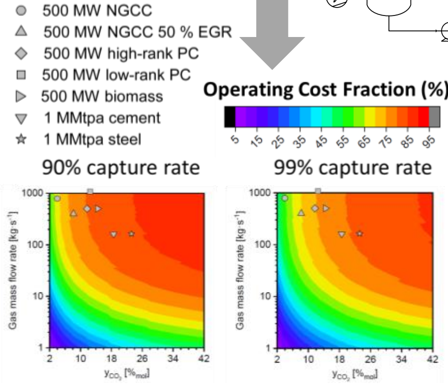
Process modelling
Develop understanding of the impacts on cost and technical performance

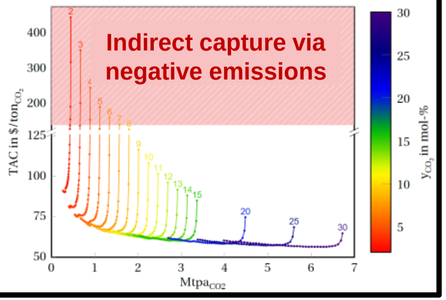
Process modelling in gPROMS and MATLAB

MATLAB



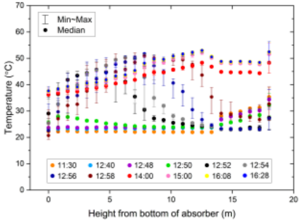
gPROMS



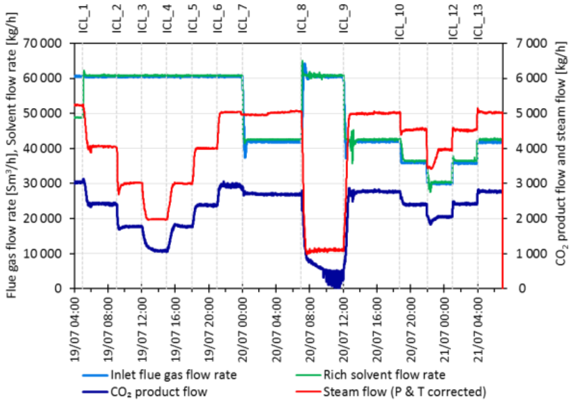


Demonstration
Demonstrates feasibility and develop understanding of plant operation

CO_2 TECHNOLOGY CENTRE MONGSTAD



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., et al., (2020). International Journal of Greenhouse Gas Control, 93, 102879.
IEAGHG, 2022. Start-Up and Shutdown Protocol for Natural Gas-Fired Power Stations with CO_2 Capture", technical report 2022-08, 2022.

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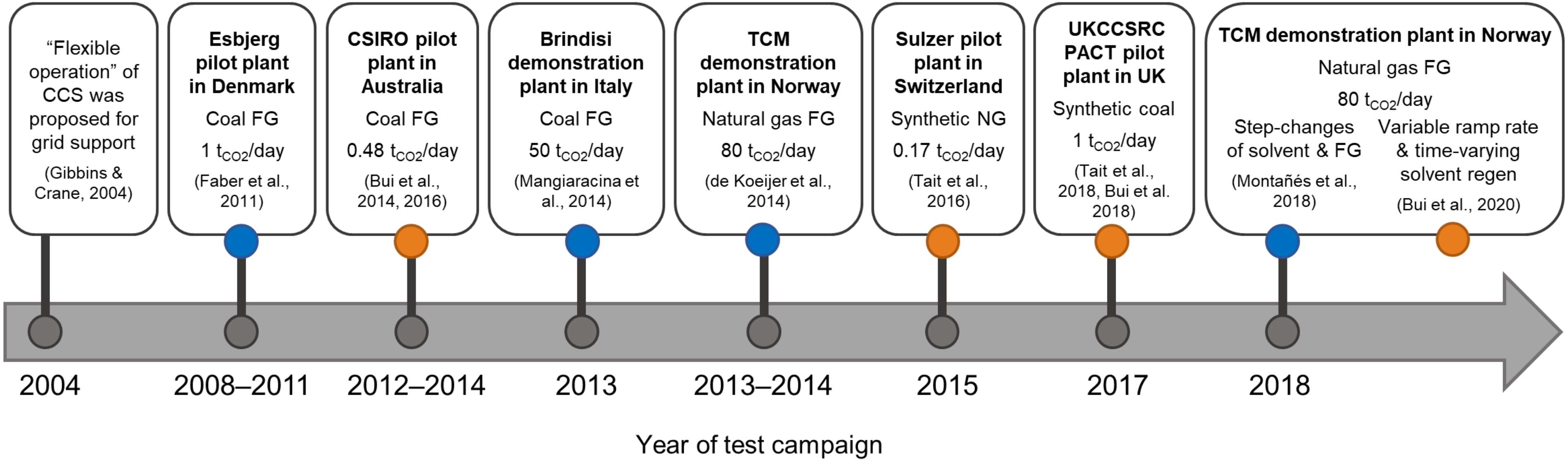
Pilot & demonstration studies of flexible CCS operation



Dynamic process data unavailable

Dynamic process data published

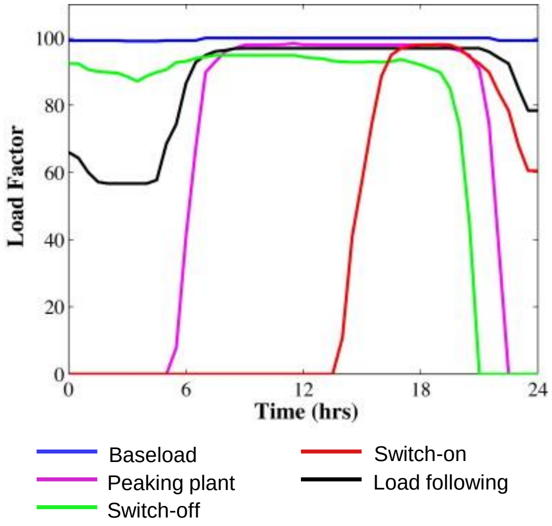
We have gained valuable operating experience at dynamic conditions.

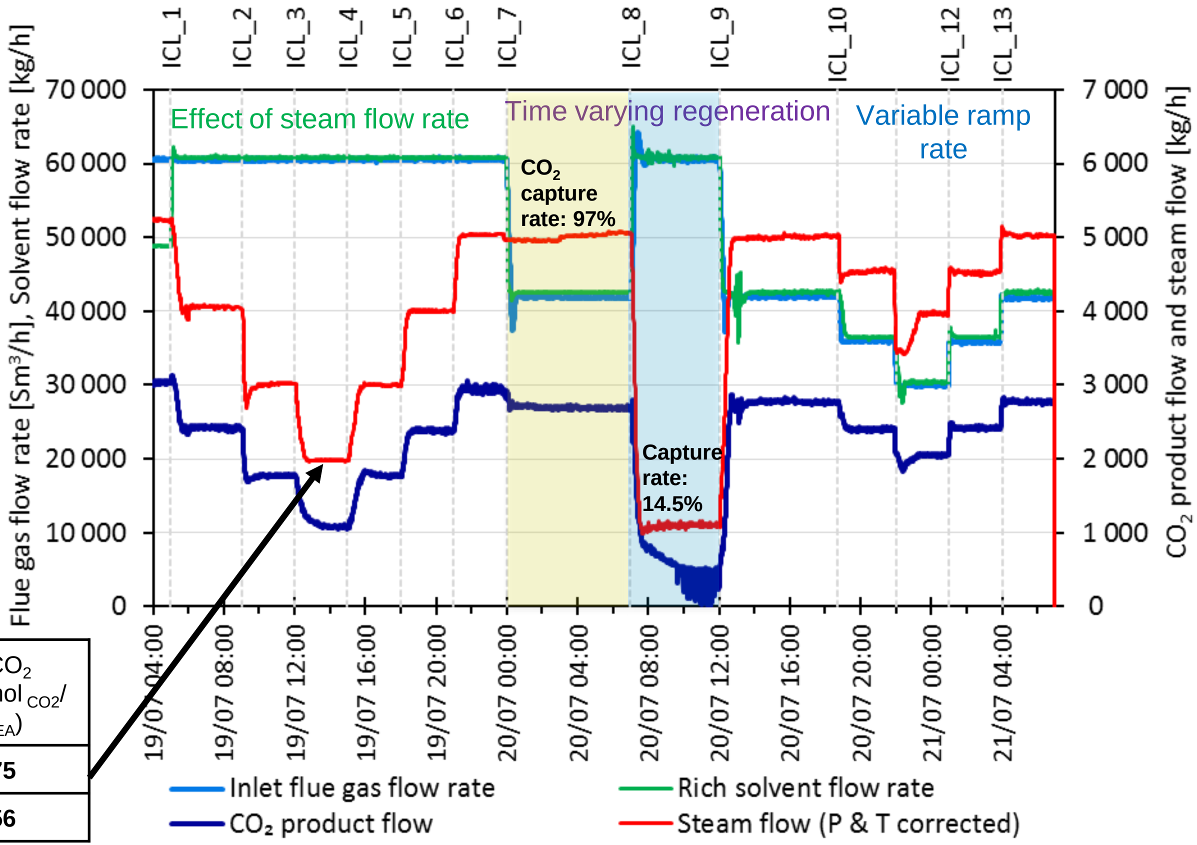
Dynamic operating data for model development is being made available.

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

Flexibility of power plants with CCS

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





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**

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.
Bui, M., et al., (2020). International Journal of Greenhouse Gas Control, 93, 102879.

Flexible operation of a demonstration-scale CO_2 capture plant

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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.

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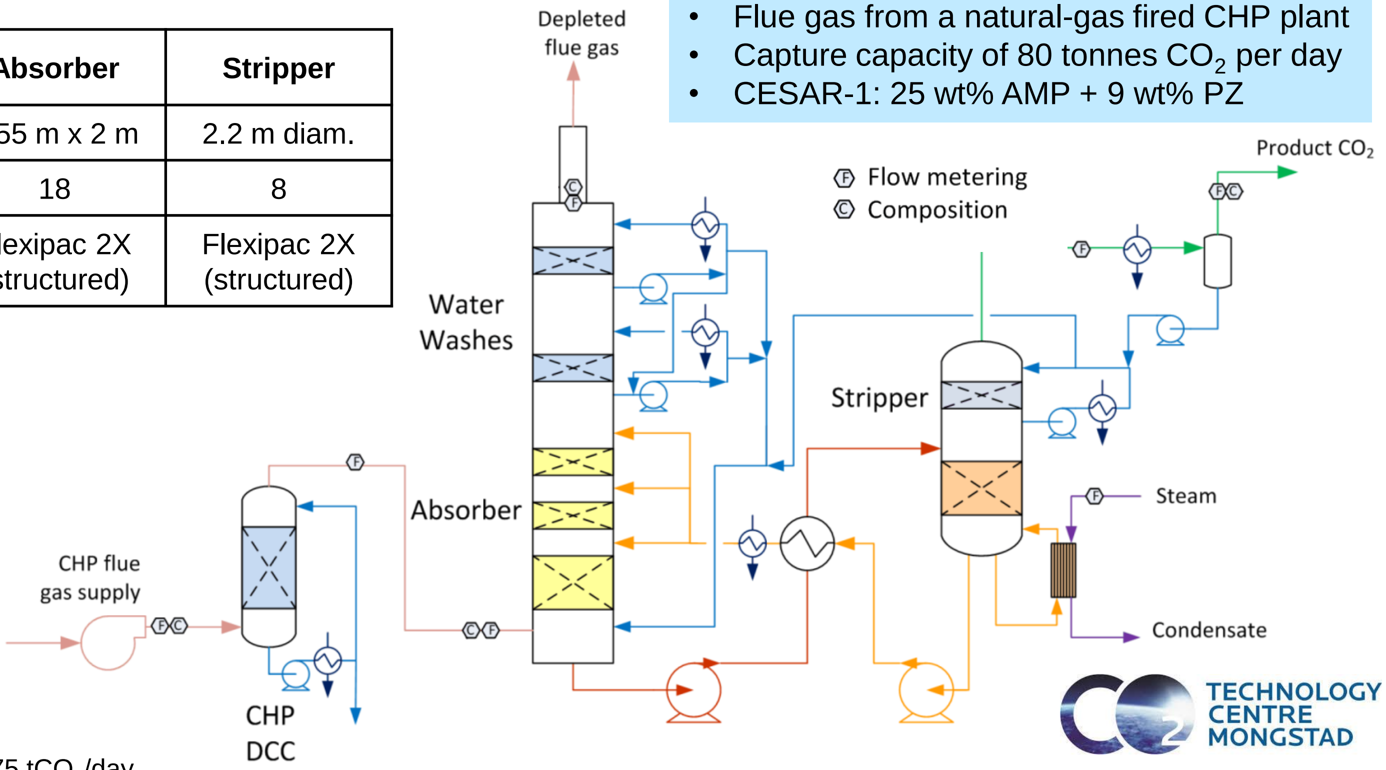
	Absorber	Stripper
Cross section dimensions	3.55 m x 2 m	2.2 m diam.
Packing height (m)	18	8
Packing type	Flexipac 2X (structured)	Flexipac 2X (structured)

Flue gas component	CHP
	mole %
N_2	71.6 – 78.6
CO_2	3.5 – 4.3
H_2O	2.5 – 6.3
O_2	12.5 – 14.4
Ar	0.9 – 1.0

RCC mode: gas 12 mol% CO_2, captures 275 tCO_2/day

Combined heat and power (CHP) mode

- Flue gas from a natural-gas fired CHP plant
- Capture capacity of 80 tonnes CO_2 per day
- CESAR-1: 25 wt% AMP + 9 wt% PZ



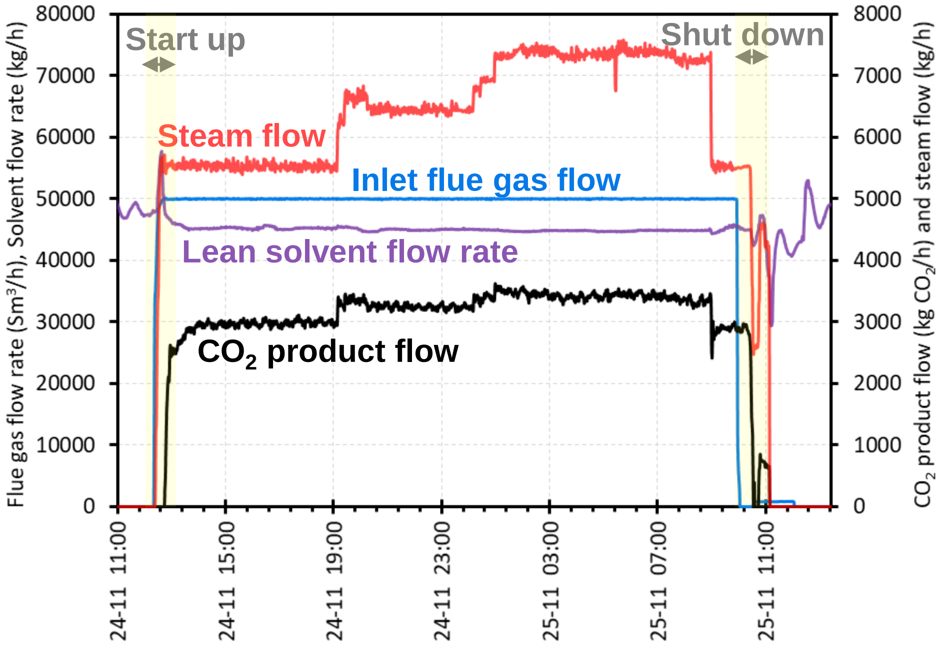
TECHNOLOGY CENTRE MONGSTAD

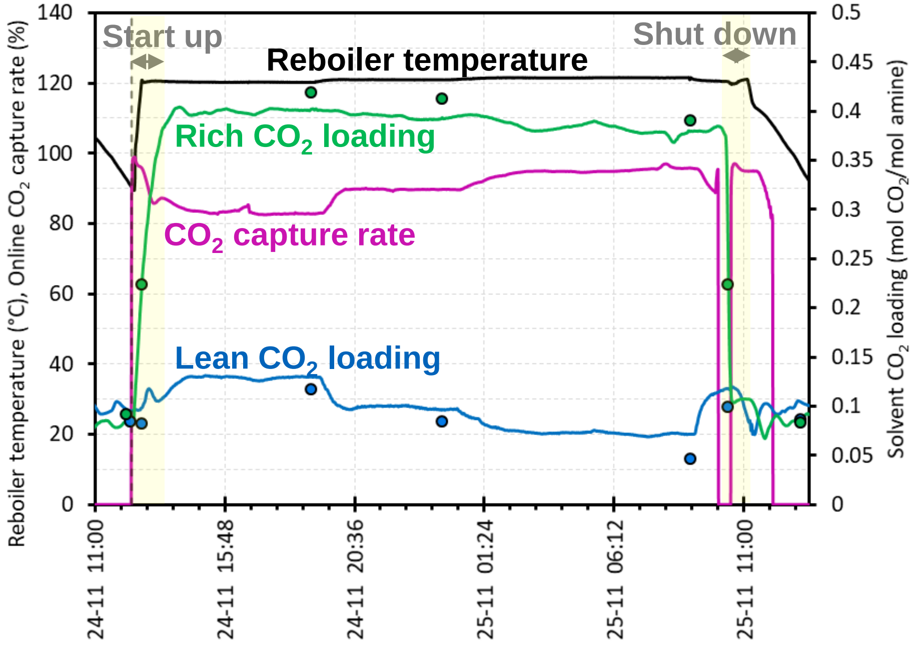
The 18 m packing height used for these test corresponds to the bottom two beds
Total height of all three beds = 24 m

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

Start-up and shut down tests at TCM

Hot start-up and shut down with 53 m^3 solvent inventory





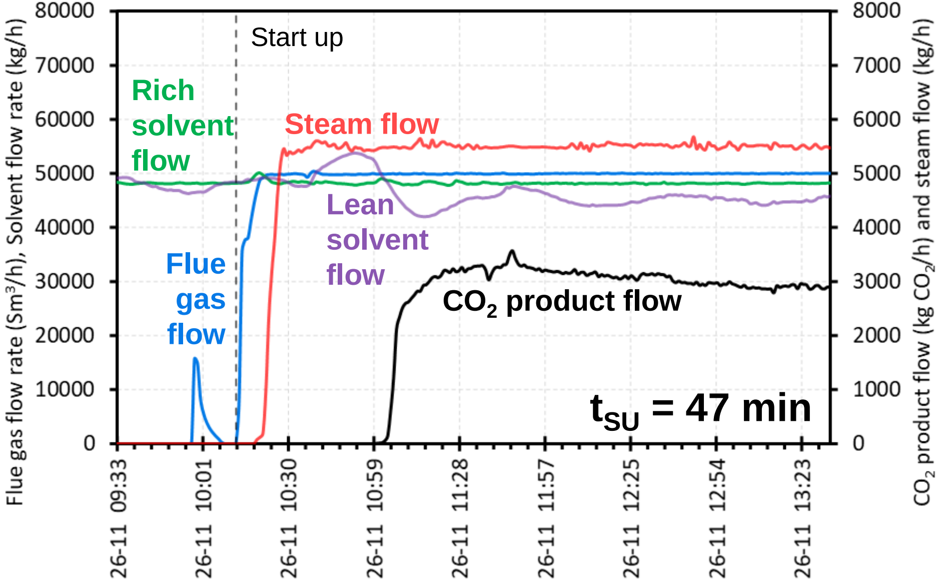
Start up: Flue gas flow is turned on, steam flow begins earlier, at same time, or delayed.

Shut down: Flue gas flow ramps down, steam flow rate continues until target solvent loading is achieved.

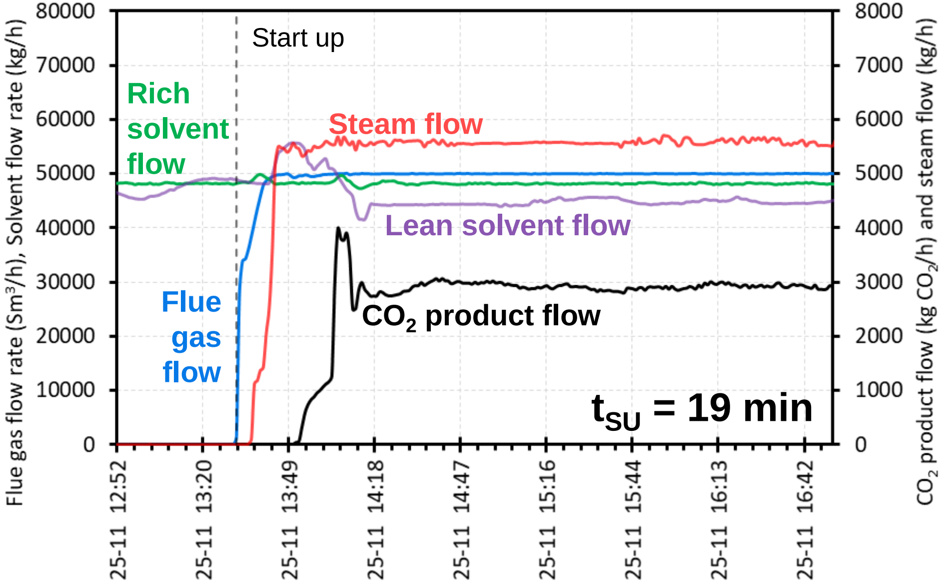
Bui & Mac Dowell, 2022. Start-Up and Shutdown Protocol for Natural Gas-Fired Power Stations with CO_2 Capture", IEAGHG technical report 2022-08, August 2022.

Cold vs hot start-up

Cold start-up with 42 m³ solvent inventory



Hot start-up with 42 m³ solvent inventory



Cold start-up: performed after a long downtime, i.e., >8 hours, stripper cools to near ambient temperature (25 – 40 °C). The time when CO_2 product flow starts is t_{SU}. Test above has steam flow starting at a similar time to the flue gas flow.

Hot start-up: performed after a short downtime, i.e., off for <8 hours, stripper is still high temperature at 80 °C or above. Thus, hot start-ups are much quicker than cold start-ups (shorter t_{SU}).

Bui & Mac Dowell, 2022. Start-Up and Shutdown Protocol for Natural Gas-Fired Power Stations with CO_2 Capture", IEAGHG technical report 2022-08, August 2022.

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Key learnings

- High capture rates above 90% is techno-economically feasible (at steady state).
- During dynamic operation, 90% capture rate is feasible with load following regimes (e.g., ramp up/down) and hot start-up and shut down.
- During cold start-up and shut down, CO_2 capture rates can reduce to 50% or lower.
- Increased start-up and shut down cycles could increase CO_2 emissions of a CCGT significantly.

	Zero emissions intensity steam		With an NG auxiliary boiler for SUSD	
82 min start-up (SU) combined with shut down (SD)	Cumulative specific reboiler duty (MJ/kg CO_2)	Cumulative CO_2 captured (%)	Cumulative specific reboiler duty (MJ/kg CO_2)	Cumulative CO_2 captured (%)
Cold SU 53 m^3 & SD	8.15	80.0	12.42	52.5
Cold SU 42 m^3 & SD	8.51	66.3	13.04	43.3
Hot SU 53 m^3 & SD	6.06	97.3	7.26	81.2
Hot SU 42 m^3 & SD	5.94	96.5	6.93	82.9
Hot SU 42 m^3 delayed steam & SD	6.17	67.7	7.35	56.8

Bui, M., et al., (2020). International Journal of Greenhouse Gas Control, 93, 102879.
IEAGHG, 2022. Start-Up and Shutdown Protocol for Natural Gas-Fired Power Stations with CO_2 Capture", technical report 2022-08, 2022.

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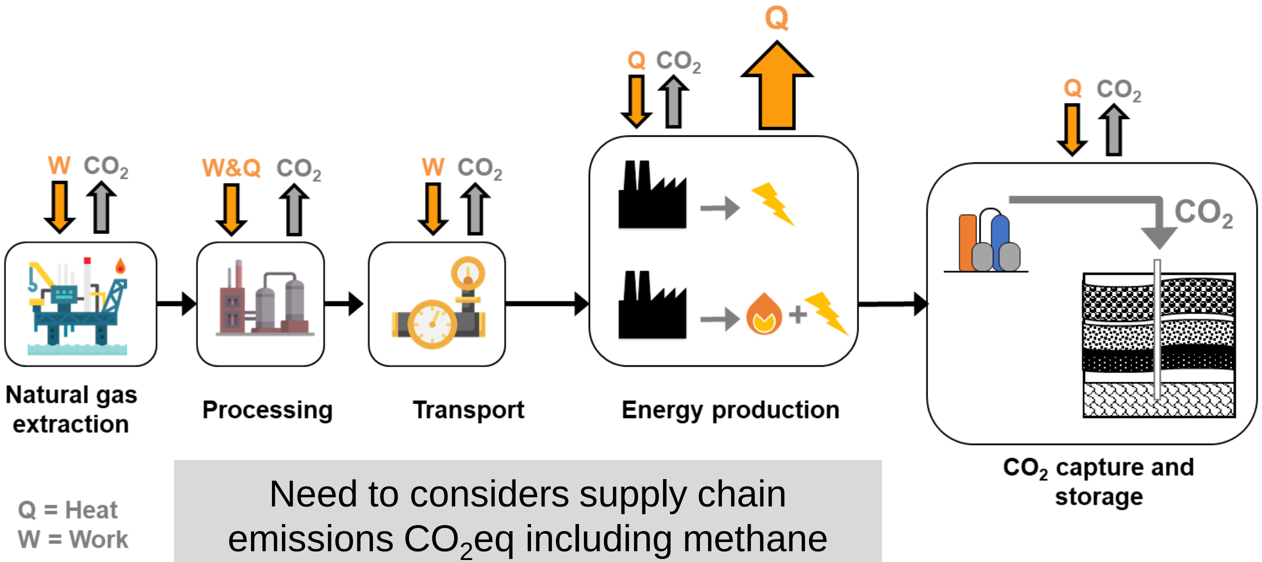
EU green taxonomy

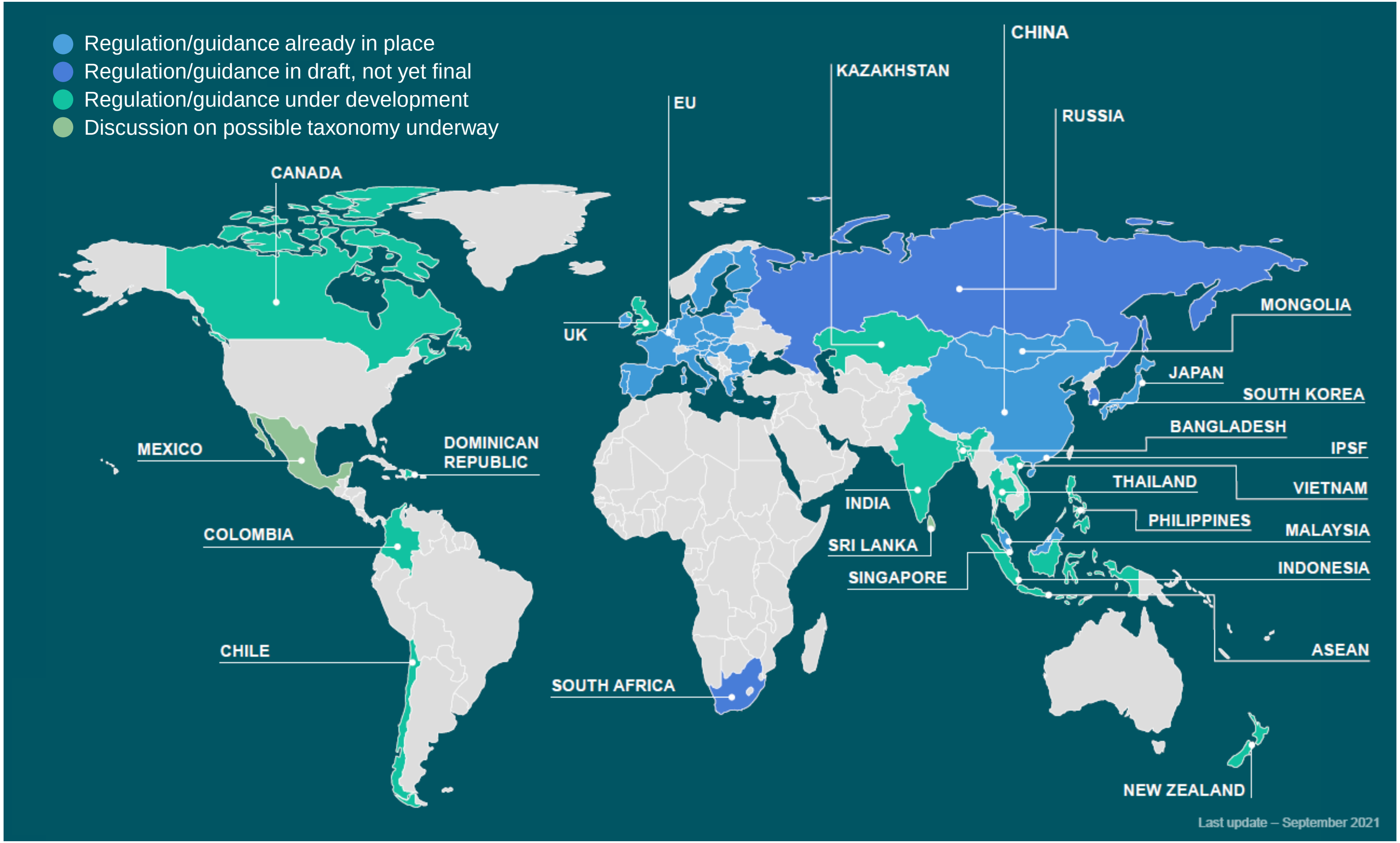


Need to considers supply chain emissions CO_2eq including methane leakage

Provides financial firms guidance on which activities qualify as being "green".

Technology-agnostic emissions threshold of 100 kg CO_2 eq/MWh for electricity generation, heat production and co-generation of heat and electricity.

For hydrogen production, the lifecycle GHG emissions threshold needs to be lower than 3 tCO_2 eq/t H_2, which favours green and blue hydrogen.



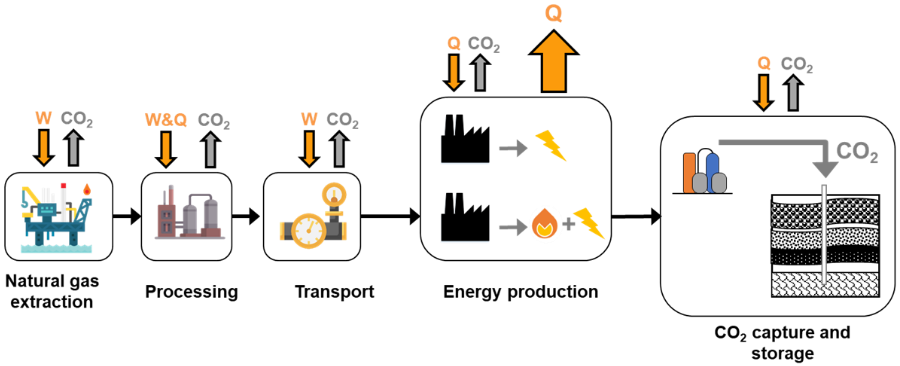
FoSDA (2021). Taxonomy Projects Around the World (Future of Sustainable Data Alliance). https://futureofsustainabledata.com/taxomania-an-international-overview/.

Carbon capture & storage: Green taxonomy

To determine the eligibility of a combined cycle gas turbine (CCGT) power plants within any future sustainable green taxonomy.

Evaluated the effect of the following factors on the CO_2 intensity of electricity generation by a CCGT power plant:

- Natural gas supply chain emissions;
- CO_2 capture rate;
- Switching to blue hydrogen;
- Number and type (e.g., cold vs hot) of start-up and shut down cycles.



Natural gas CCGT-CCS

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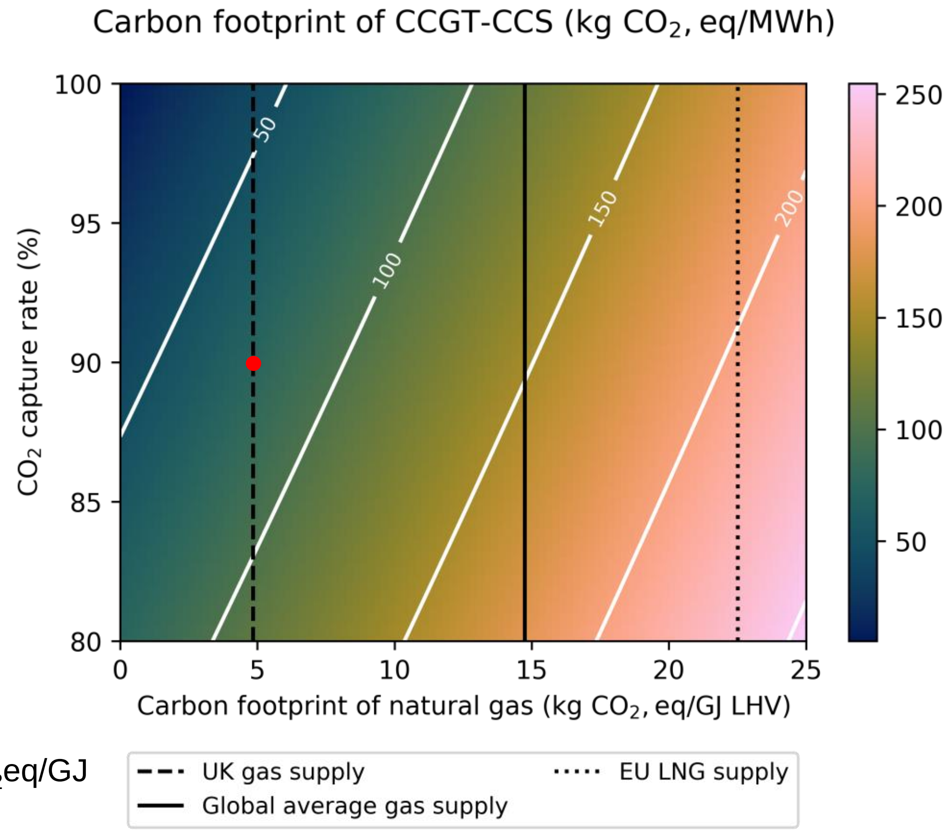

At steady state operation, a CCGT-CCS plant using UK gas would need to capture 82.5% of the CO_2 to meet the 100 kg CO_2eq/MWh_{el} criteria.

The steady state CO_2 intensity of a CCGT-CCS using UK gas with a 90% capture rate is **75.2 kg CO_2eq/MWh_{el}.**

UK supply chain carbon footprint of natural gas = 4.9 kg CO_2eq/GJ LHV (Wernet et al. 2019)

Hydrogen CCGT-CCS

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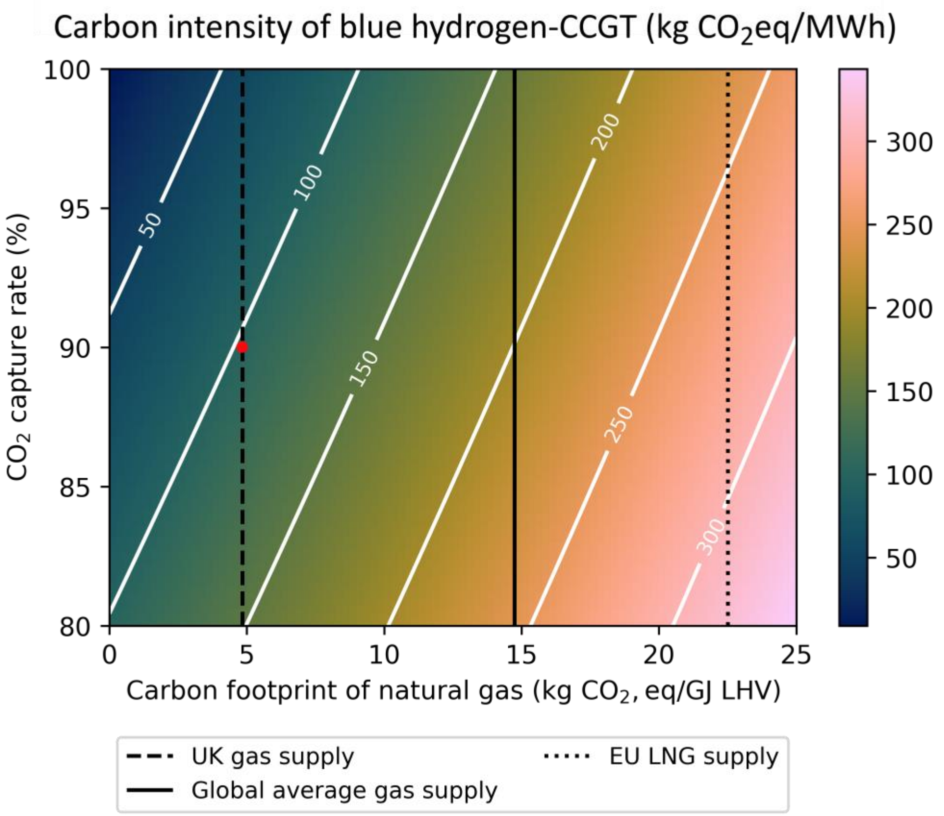
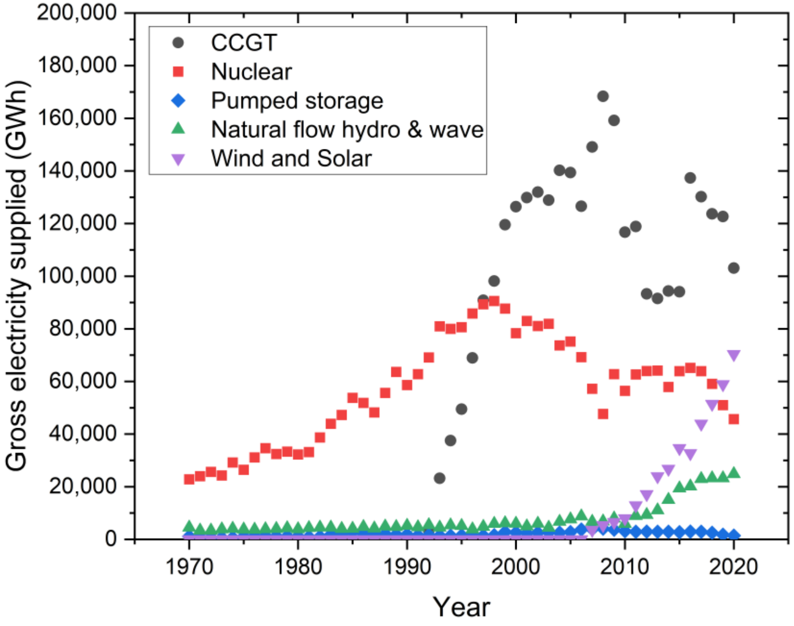
Using UK natural gas for SMR retrofitted with CCS and capturing 90% CO_2 to produce hydrogen for a steady state CCGT results in a CO_2 intensity of **103 kg CO_2 eq/MWh_{el}.**

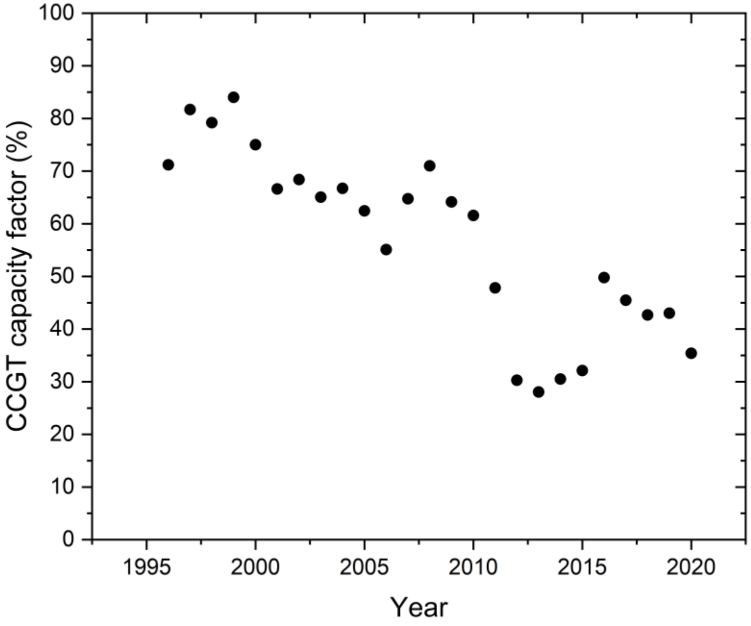
To satisfy the green taxonomy, need to use: (i) >91% CO_2 capture rate, (ii) reduce natural gas supply chain emissions, or (iii) use green hydrogen.

Assuming a CO_2 capture rate of 95% could achieve 80 kg CO_2 eq/MWh_{el} with a blue hydrogen-CCGT.



Gross electricity supply and average annual capacity factor of UK gas-CCGT plants

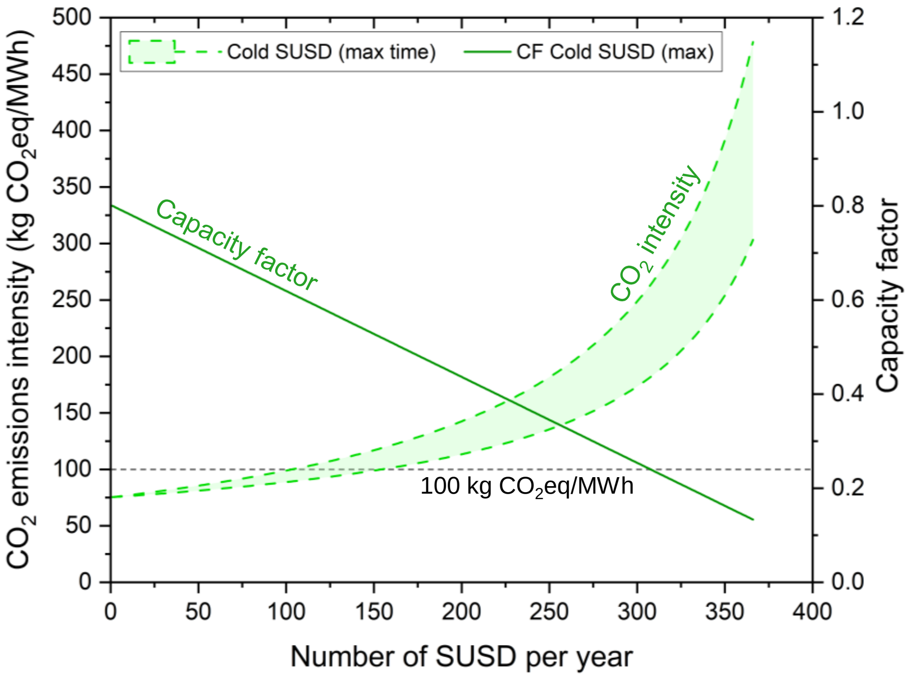


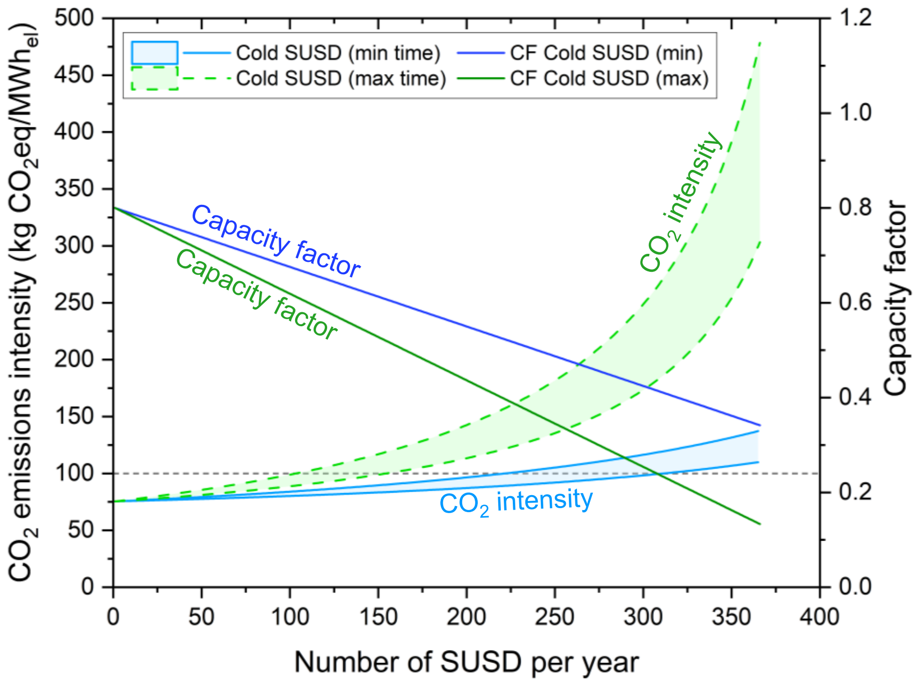


https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes

Effect of start-up & shut down on CCGT-CCS emissions

The EU taxonomy proposes an overarching, technology-agnostic emissions threshold of 100 kg CO_2 eq/MWh for electricity generation, heat production and co-generation of heat and electricity.





M. Bui, N. Sunny and N. Mac Dowell, (2023), The prospects of flexible natural gas-fired CCGT within a green taxonomy. iScience, 26, 107382. https://doi.org/10.1016/j.isci.2023.107382

Effect of start-up & shut down on CCGT-CCS emissions

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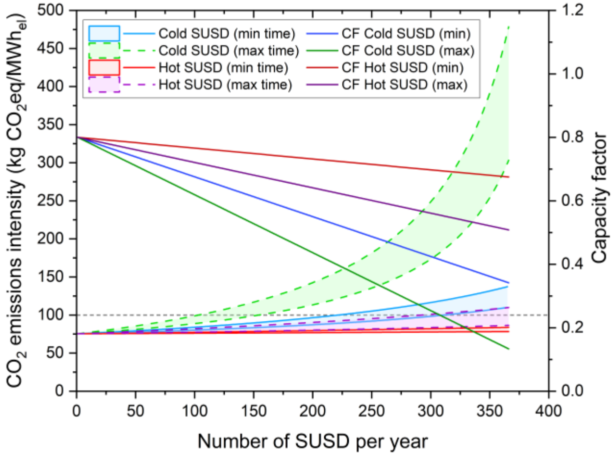
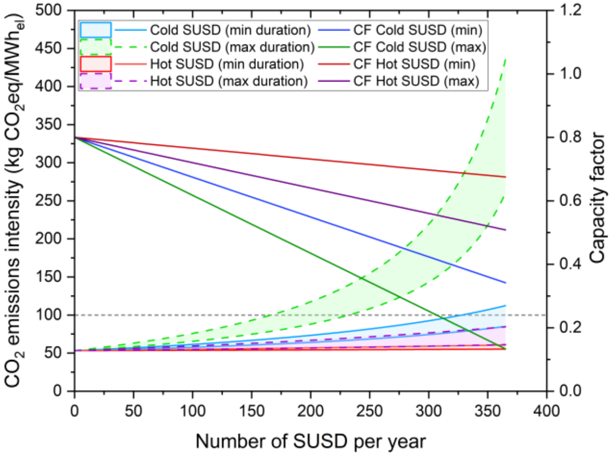
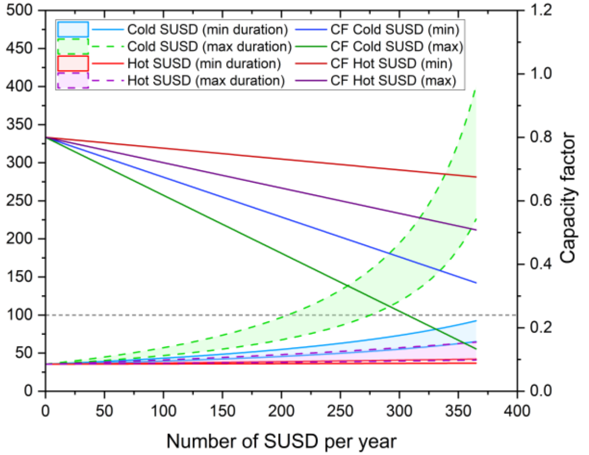
90% capture rate



95% capture rate



99% capture rate



As the number of SUSD cycles increases, the CO_2 emissions intensity becomes increasingly higher, and the capacity factor reduces. Higher CO_2 capture rates ensures that taxonomy emissions threshold can be met during flexible operation.

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NG CCGT-CCS: Green taxonomy

To remain below 100 kg CO_2eq/MWh_{el}

	Number of start-up and shut down cycles	
90% capture @ steady state	NG auxiliary boiler	Zero emissions aux boiler
Cold SUSD (min duration)	221	311
Cold SUSD (max duration)	102	153
Hot SUSD (min duration)	No limit	No limit
Hot SUSD (max duration)	291	No limit

	Number of start-up and shut down cycles	
95% capture @ steady state	NG auxiliary boiler	Zero emissions aux boiler
Cold SUSD (min duration)	328	No limit
Cold SUSD (max duration)	166	232
Hot SUSD (min duration)	No limit	No limit
Hot SUSD (max duration)	No limit	No limit

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Conclusions

With higher penetration of renewable energy, thermal power plants with CCS could have an important role in providing low carbon, dispatchable electricity.

Understanding the potential impact of key process decisions on the prospects of existing and future fossil fuel-based power generation under a green taxonomy will be essential to ensure a cost-effective transition to net zero.

For NG CCGT-CCS, key considerations include reducing methane leakage, high CO_2 capture rates, and minimising the impacts of start-up and shut down cycles performed by the CCGT-CCS plant.

The main advantage of hydrogen-fired CCGT is that SUSD and highly flexible operation will not increase the CO_2 emissions intensity of the electricity. However, the hydrogen fuel needs to be highly carbon efficient to meet the EU taxonomy.

In order for natural gas to play an enduring role in the transition towards net zero, managing GHG emissions from both the upstream natural gas supply chain and the conversion facility is key.

The ability to maximise the CO_2 capture during start-up and shut down reduces residual CO_2 emissions, thus easing the need for CO_2 removal offsets, e.g., from bioenergy with CCS or direct air capture technologies.

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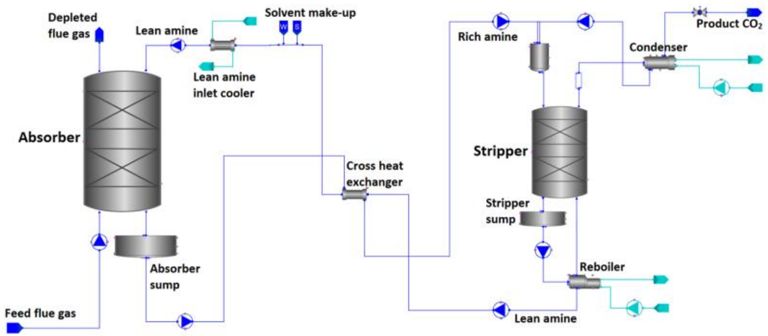
Conclusions and future work

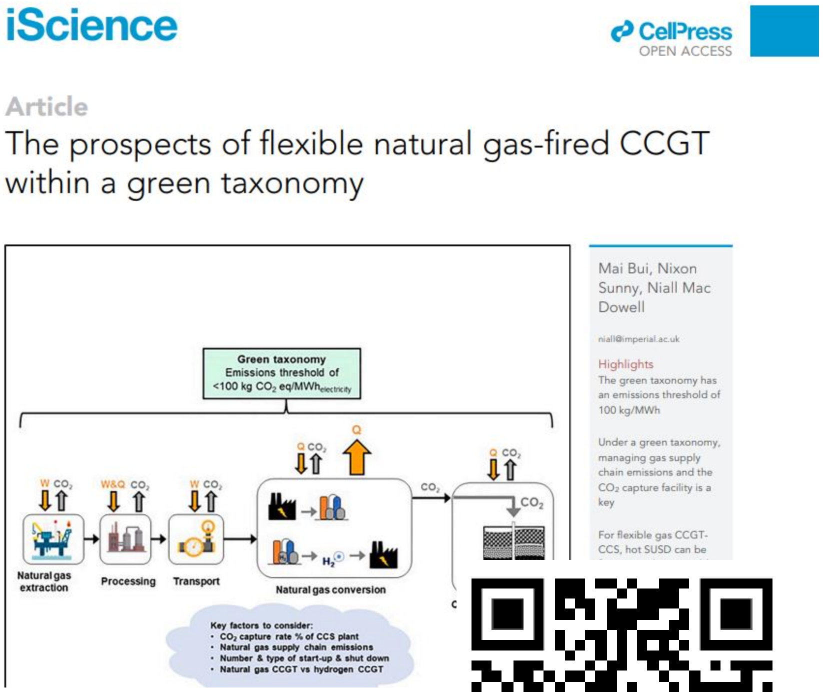
These learnings will help improve the performance of flexible operation and SUSD strategies in CO_2 capture plants.

The data from this study will help in the development more robust process control systems, as well as improve the description of flexible and dynamic operation in process & systems models.

Future work:

- Investigate the impact of different process configurations and process control systems that could improve plant flexibility and SUSD performance, e.g., via process modelling.
- Effect of different solvent types on CO_2 capture plant flexibility and SUSD performance.
- Study dynamic interactions between the power plant and CCS process, also upstream/downstream effects.
- Techno-economic analysis to understand the cost implications of different SUSD strategies.
- Understand the impact of SUSD cycles at a systems scale, i.e., effect on ability to reach net zero.

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The prospects of flexible natural gas-fired CCGT within a green taxonomy

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Highlights

The green taxonomy has an emissions threshold of 100 kg/MWh

Under a green taxonomy, managing gas supply chain emissions and the CO_2 capture facility is a key

For flexible gas CCGT-CCS, hot SUSD can be

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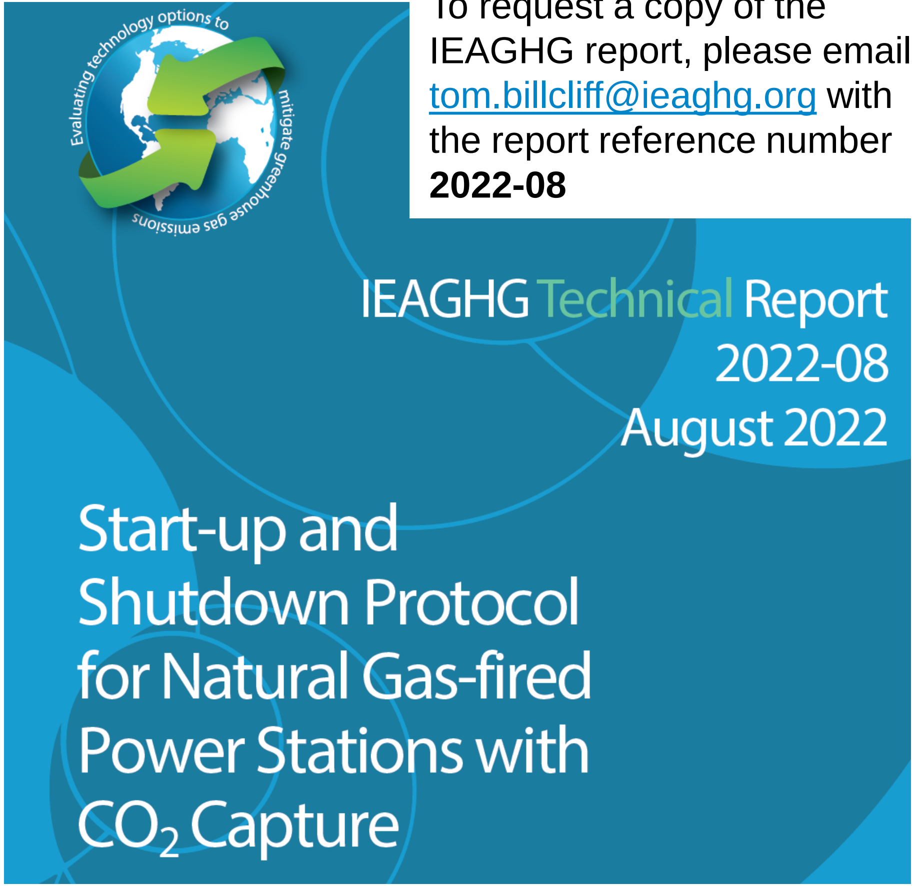

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IEAGHG, Start-Up and Shutdown Protocol for Natural Gas-Fired Power Stations with CO_2 Capture", IEAGHG technical report 2022-08, August 2022.

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Appendix

Flexibility Requirements of gas power plants

		OCGT	Recips	CCGT
Efficiency	%	<40%	<40%	<63%
Plant size	MW	1 – 299	5 – 49	500 to 2500
Location / scale		Utility or industrial, centralised or decentralised	Industrial	Centralised / utility
Operating mode		Peaking	Peaking	Baseload / shifting
Number of starts	#	350 – 700	350 – 700	50 – 300
Hours per year	hrs/yr	500 – 2000	500 – 2000	4000 – 8500
Start time to min load	mins	5 – 10	3 – 4	20 – 90
Start time to max load	mins	20 – 30	6 – 10	60 – 180
CCS connection Plant retrofit Plant new build		 ☹ 😐	 ☹ 😐	 😐 ☺

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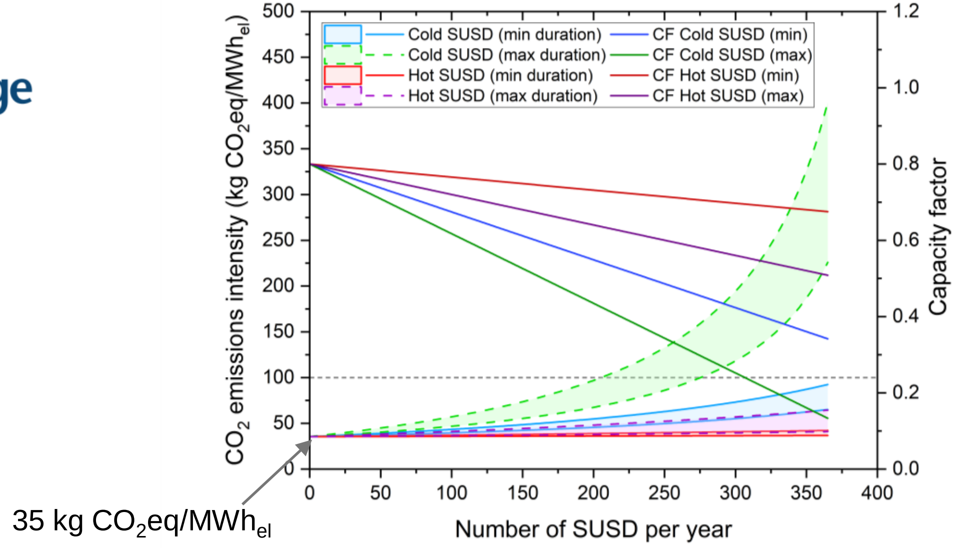

	Number of start-up and shut down cycles	
99% capture @ steady state	NG auxiliary boiler	Zero emissions aux boiler
Cold SUSD (min duration)	No limit	No limit
Cold SUSD (max duration)	205	275
Hot SUSD (min duration)	No limit	No limit
Hot SUSD (max duration)	No limit	No limit

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CCGT-CCS: Effect of start-up & shut downs

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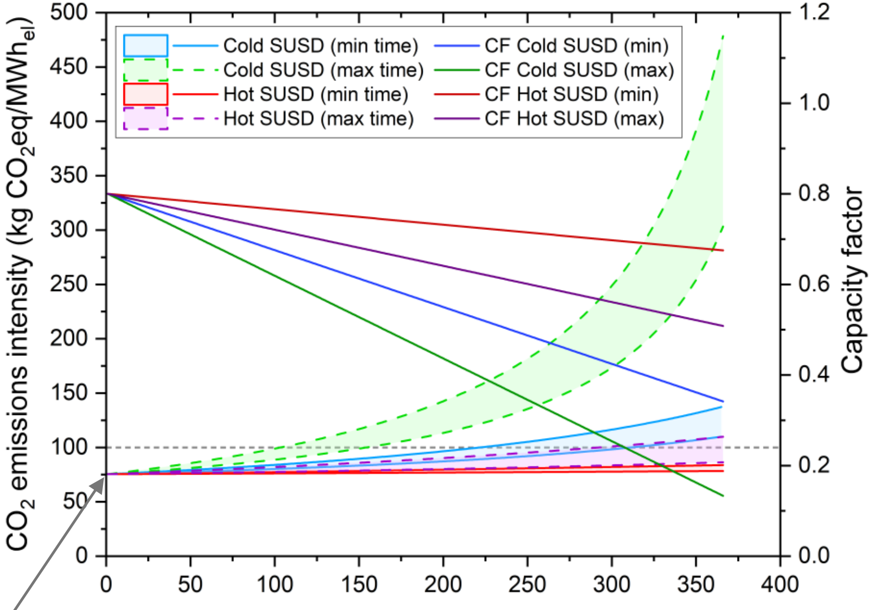
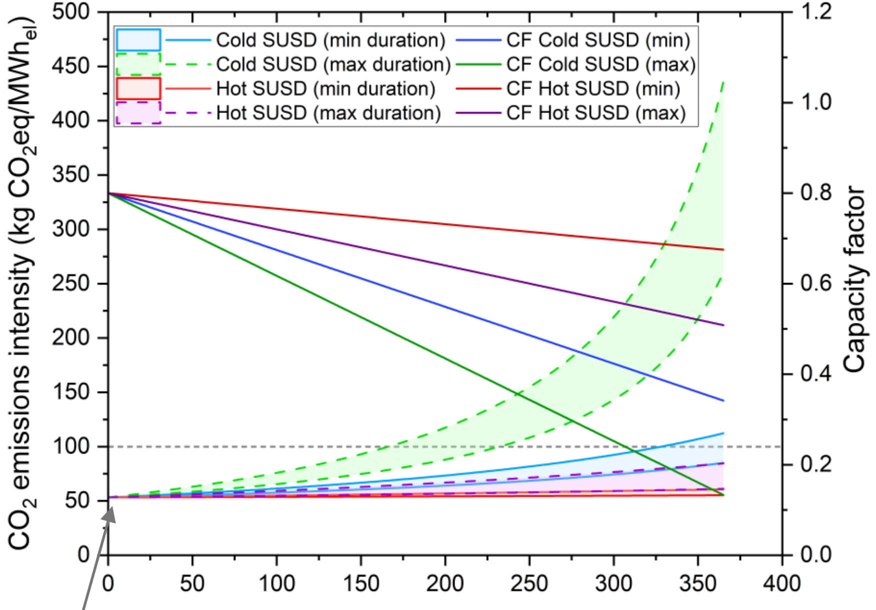
90% capture during steady state periods



75 kg CO_2eq/MWh_{el}

95% capture during steady state periods



53 kg CO_2eq/MWh_{el}

M. Bui, N. Sunny and N. Mac Dowell, (2023), The prospects of flexible natural gas-fired CCGT within a green taxonomy. iScience, 26, 107382. https://doi.org/10.1016/j.isci.2023.107382

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Characteristics of start-up and shut down types

Start-up & shut down type	Duration of one start-up & shut down cycle (h)	Downtime (h)	Cumulative CO_2 capture rate with zero CO_2 intensity auxiliary boiler (%)	Cumulative CO_2 capture rate, accounts for NG CO_2 intensity of auxiliary boiler (%)	Duration of time using auxiliary boiler for SUSD (h)
Cold start-up + shut down (Min time)	3	8	73.15	47.9	2
Cold start-up + shut down (Max time)	8	8	73.15	47.9	5
Hot start-up + shut down (Min time)	2	1	96.9	82.05	1.33
Hot start-up + shut down (Max time)	6	1	96.9	82.05	4.33

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EU green taxonomy

- Provides financial firms guidance on which activities qualify as being “green”.
- It is a common classification framework, provides a list of economic activities that will contribute to climate change mitigation and minimise environmental harm.
- In the EU, the green taxonomy proposes an overarching, technology-agnostic emissions threshold of 100 kg CO_2 eq/MWh for electricity generation, heat production and co-generation of heat and electricity.
- For hydrogen production, the lifecycle GHG emissions threshold needs to be lower than 3 tCO_2 eq/t H_2, which favours green and blue hydrogen.
- Unabated fossil fuel-fired power plant (i.e., without CCS) will not meet the required carbon emission threshold.