APGTF Workshop: Power generation (coal, gas, and biomass) under increasingly stringent emissions regulations
Tuesday 6th December, IET, Savoy Place, London

Suitability of CCS plants to meet future emission limits

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www.ukccsrc.ac.uk

The UKCCSRC is supported by the Engineering and Physical Sciences Research Council as part of the Research Councils UK Energy Programme

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Pioneering research and skills

About the UKCCSRC

www.ukccsrc.ac.uk

The UK Carbon Capture and Storage Research Centre (UKCCSRC) **leads and coordinates a programme of underpinning research on all aspects of carbon capture and storage** (CCS) in support of basic science and UK government efforts on energy and climate change.

The Centre brings together over **290 of the UK's world-class CCS academics** from moe than 40 UK universities and research institutes and provides a **national focal point for CCS research and development**.

Over **310 Early Career Researchers** participate in an active **capacity development ECR programme.**

Initial core funding for the UKCCSRC is provided by £10M from the Engineering and Physical Sciences Research Council (EPSRC) as part of the RCUK Energy Programme. This is complemented by £3M in additional funding from the Department of Energy and Climate Change (DECC, now BEIS) to help establish new open-access national pilot-scale facilities (www.pact.ac.uk). Partner institutions have contributed £2.5M.

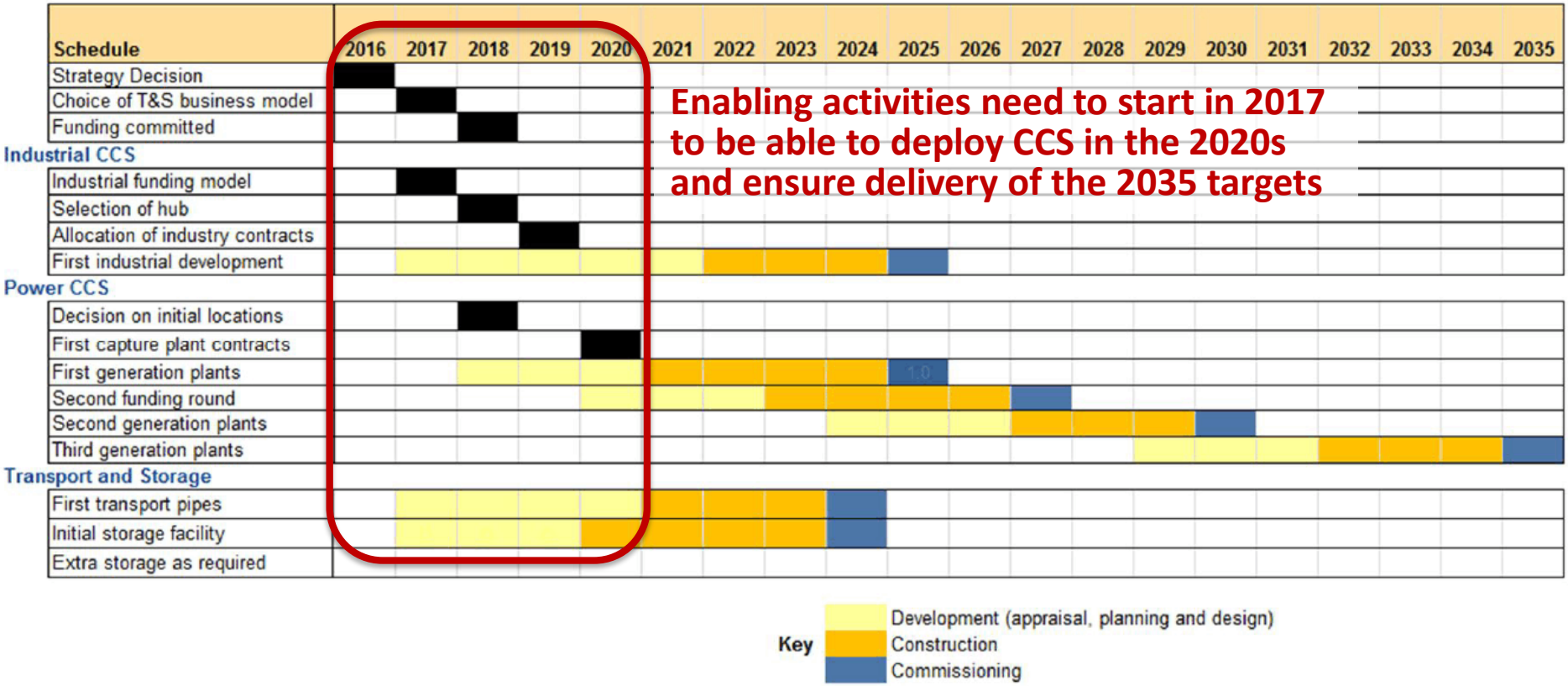
The UKCCSRC welcomes experienced industry and overseas **Associate** members and links to all CCS stakeholders through its **CCS Community Network**.
https://ukccsrc.ac.uk/membership/associate-membership
https://ukccsrc.ac.uk/membership/ccs-community-network

Committee on Climate Change May/June 2016: A strategic approach for developing CCS in the UK

https://www.theccc.org.uk/wp-content/uploads/2016/07/Poyry_-_A_Strategic_Approach_For_Developing_CCS_in_the_UK.pdf
https://www.theccc.org.uk/publication/meeting-carbon-budgets-2016-progress-report-to-parliament/

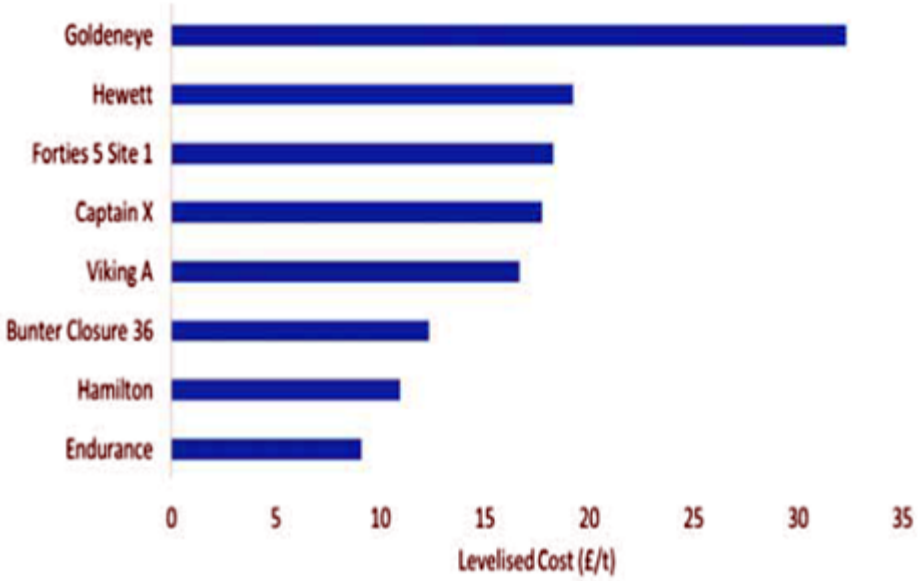
'**Sufficient scale of targeted roll-out**: a combination of industry and power plants is necessary to realise economies of scale and allow a build-up of skills, developer and financial interest. Our analysis suggests that an overall scale of 4-7 GW of power CCS and 3-5 Mt captured CO_2 from industrial plants by 2035 would be sufficient to commercialise CCS and facilitate subsequent wide-scale deployment.'

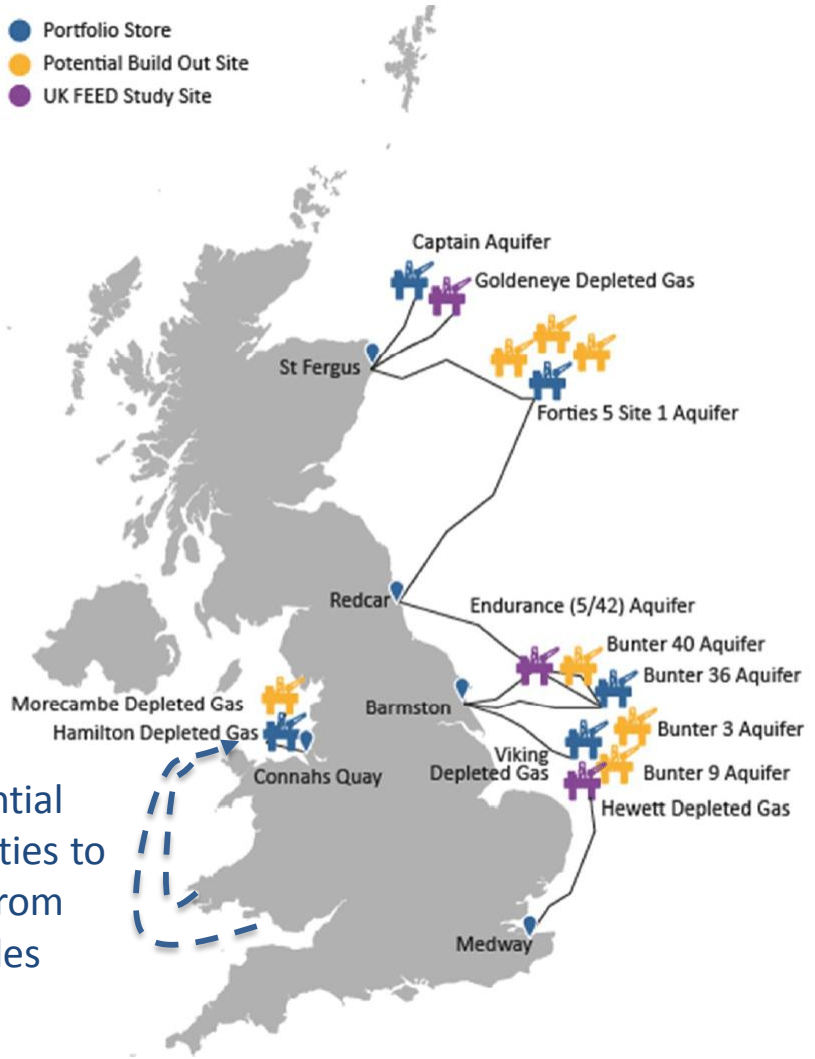
'**An initial focus on one or two strategic clusters**: clusters in areas of industrial activity around storage sites that have been identified and successfully characterised.'



ETI Strategic UK CCS Storage Appraisal Project

http://www.eti.co.uk/project/strategic-uk-ccs-storage-appraisal/



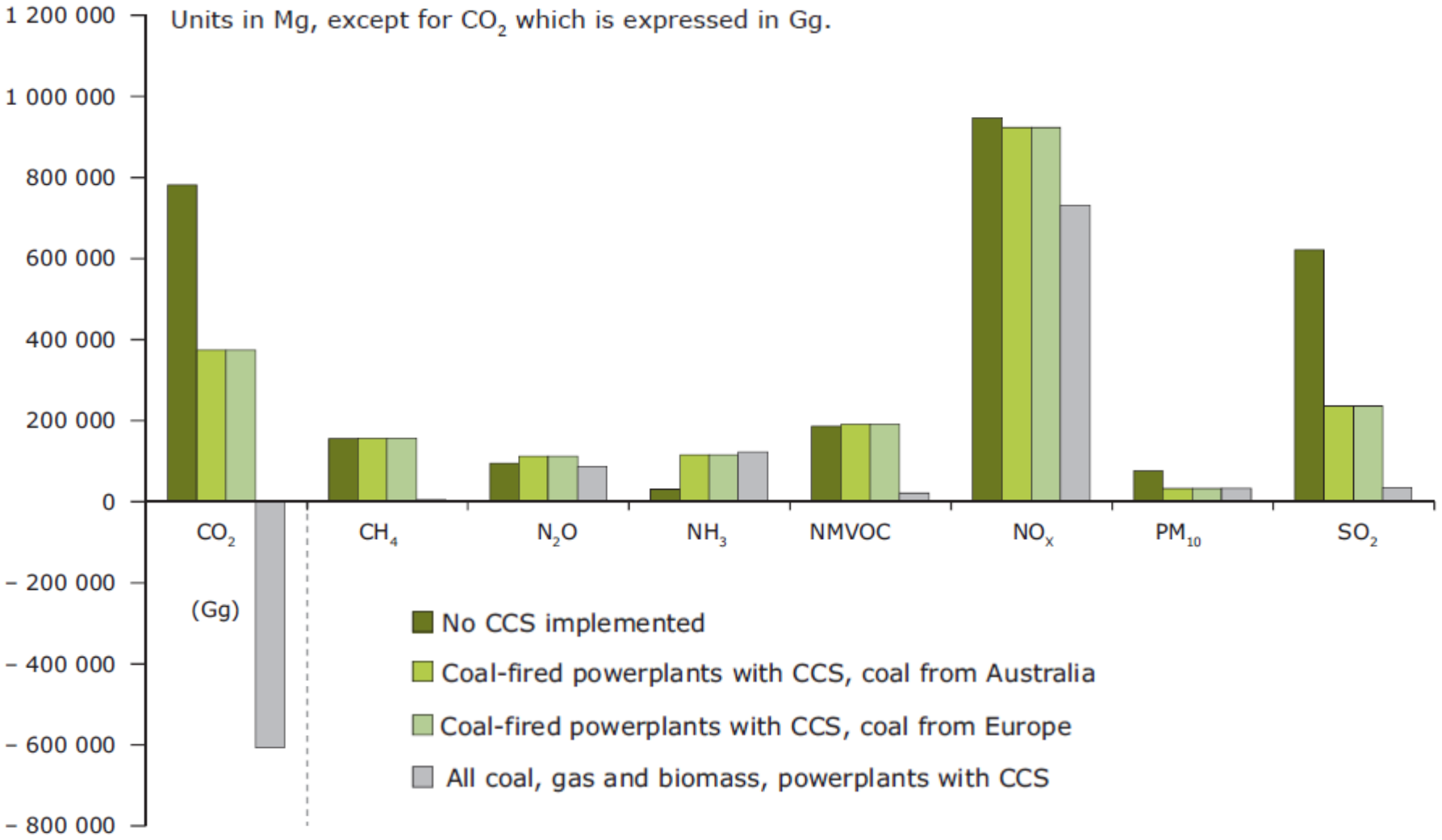


Also potential opportunities to ship CO_2 from South Wales

General expectations for emissions are encouraging

European Environment Agency Technical report No 14/2011, Air pollution impacts from carbon capture and storage (CCS) www.eea.europa.eu/publications/carbon-capture-and-storage/download

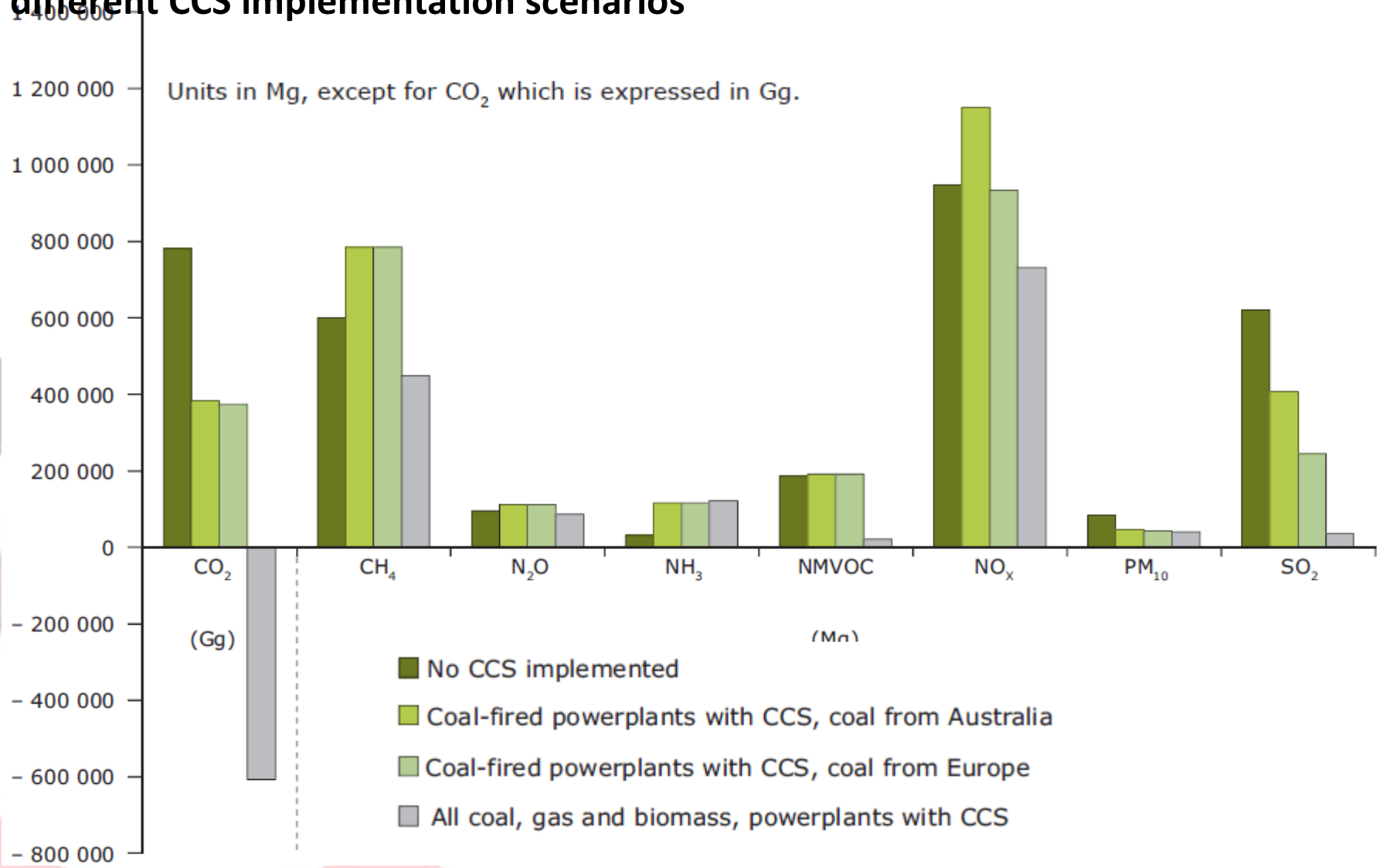
Direct emissions from power generation in 2050 under the different CCS implementation scenarios



General expectations for emissions are encouraging

European Environment Agency Technical report No 14/2011, Air pollution impacts from carbon capture and storage (CCS) www.eea.europa.eu/publications/carbon-capture-and-storage/download

Direct plus indirect emissions from power generation in 2050 under the different CCS implementation scenarios



European Environment Agency Technical report No 14/2011, Air pollution impacts from carbon capture and storage (CCS)
www.eea.europa.eu/publications/carbon-capture-and-storage/download

Overall, CO_2 emissions decrease by approximately 60 % by applying CCS to all coal-fired power plants in Europe compared to the non-CCS scenario. The additional CO_2 emissions from the transport of additional coal are negligible compared to the overall direct emissions arising from the power-generating facilities. **Implementation of CCS to all coal-, natural gas- and biomass-fuelled power plants leads to CO_2 emissions becoming negative in 2050.** This is due to the increase in biomass use between 2040 and 2050 according to the PRIMES and TIMER/IMAGE fuel mix assumptions. In this most extreme scenario, the power sector is effectively converted into a net CO_2 sink. This obviously assumes that all biomass is harvested in a sustainable way, not leading to any carbon stock changes in the European or international forests and agriculture sectors.

The CH_4 emissions are for the most part caused by the mining of coal. These emissions will increase for scenarios 2 and 3 relative to the non-CCS scenario because of the additional coal needed to compensate for the CCS fuel penalty. Where these emissions will occur geographically will depend upon the location where the additional coal will be mined — i.e. either in Europe or in Australia in the scenarios used.

European Environment Agency Technical report No 14/2011, Air pollution impacts from carbon capture and storage (CCS)
www.eea.europa.eu/publications/carbon-capture-and-storage/download

The overall PM10 emissions for Europe will decrease by around 50 %. The decrease is caused by the low emission factors for CCS-equipped power plants. Low PM10 emissions are required for the CO_2 capture process in order not to contaminate the capture solvent. The fuel penalty, because of the additional energy needed for the capture process, will lead to additional PM10 emissions during the coal mining and transport stages of the CCS life-cycle, but overall these increases are smaller in magnitude than the reduction achieved at the CCS-equipped power plants.

For SO_2 emissions an even greater reduction is noted compared to the level of emission calculated under the non-CCS scenario. A deep removal of SO_2 is needed before the capture process to prevent the reaction of SO_2 with the capture solvent and to avoid potential corrosion issues within the CCS system. The transport of additional coal from Australia (or indeed any other location) will lead to an increase in SO_2 emissions from the international shipping involved to Europe. However, overall, total life-cycle SO_2 emissions will decrease as the reduction in direct emissions is larger than the increase due to the additional shipping.

European Environment Agency Technical report No 14/2011, Air pollution impacts from carbon capture and storage (CCS)
www.eea.europa.eu/publications/carbon-capture-and-storage/download

The NOx emissions from power plants remain more or less the same after the introduction of CCS, but will decrease under the scenario of implementation of CCS to all coal, natural gas and biomass power plants. On a life-cycle basis, the overall NOx emissions are foreseen to increase under the scenario where additional coal is sourced from Australia due to increased emissions from shipping.

NH_3 emissions are the only instance in which a significant increase of direct emissions compared to the non-CCS scenario is foreseen. The increase is predicted due to the degradation of the amine-based solvent that is assumed in the current literature. New solvents are under development, with potential to show less degradation. Nevertheless, compared to the present day level of emissions of NH_3 from the EU agricultural sector (around 3.5 million Mg (tonnes), or 94 % of the EU's total emissions (EEA, 2011)), the magnitude of the foreseen NH_3 increase is relatively small.

Review of amine emissions from carbon capture systems
Version 2.01
August 2015

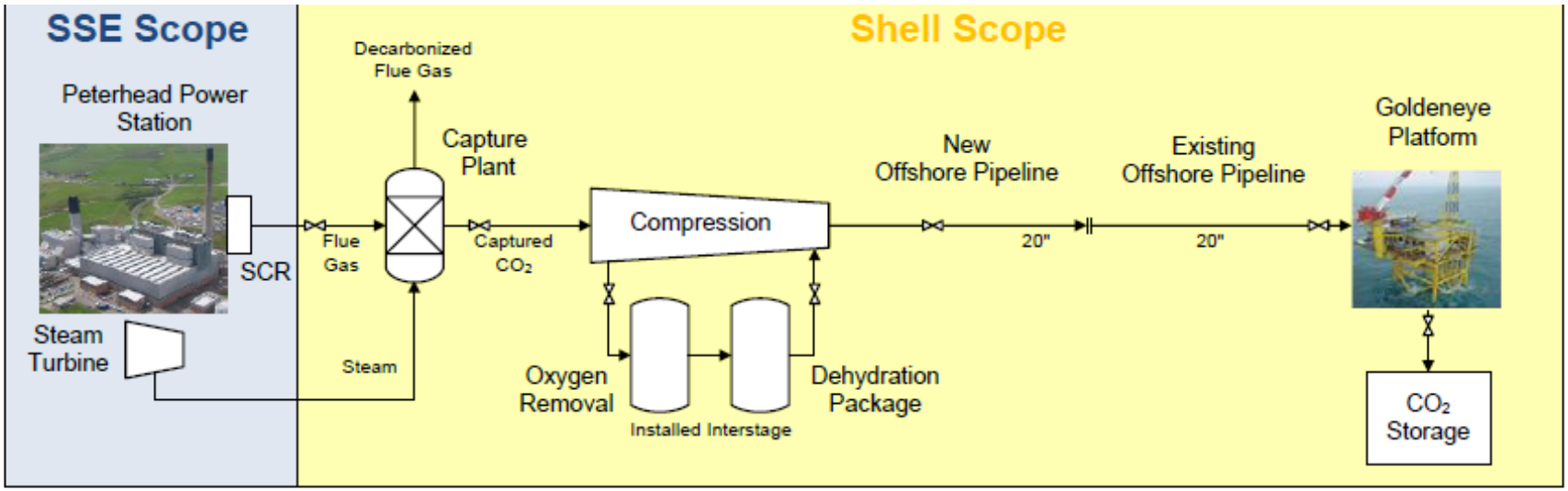
NOx

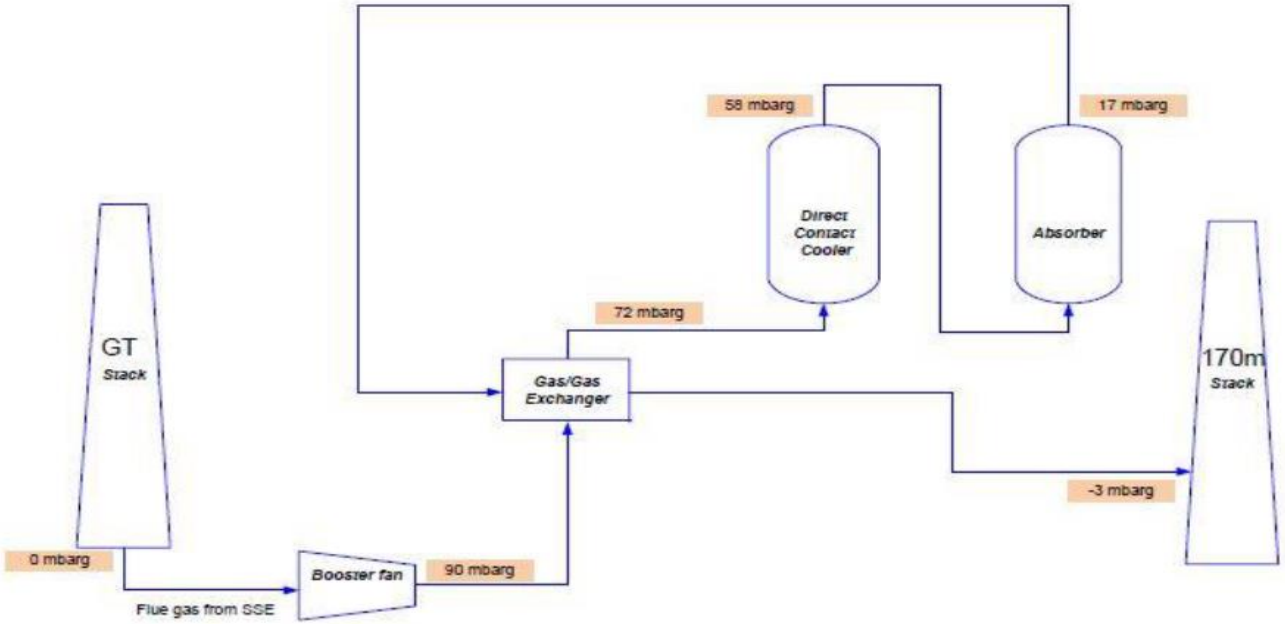
For the newest and largest coal-fired and gas-fired plants, meeting the requirements of the European Union Industrial Emissions Directive (IED) (Directive 2010/75/EU), the worst case NO_2 concentration in the absorber inlet (assuming NO_2 represents around 10% of total NOx concentrations) would be around 15mg/Nm3 for coal-fired plant. For gas-fired plant (assuming NO_2 represents up to 50% of total NOx concentrations) would be between 25 and 50mg/Nm^3. **These expected concentrations could be reduced to below 5mg/Nm^3 if a pre-scrubber polishing unit or direct contact cooler system is adopted** (IEAGHG 2011a; European IPPC Bureau, 2007).

Review of amine emissions from carbon capture systems
Version 2.01
August 2015

NH_3: The actual emissions of ammonia mainly depend on the absorber temperature. Ammonia arises from the oxidative degeneration of amines (Mertens et al, 2012). These emission concentrations would represent a high annual amine degradation rate which would increase with increasing NOx concentration at the inlet of the scrubber system (Pedersen et al., 2010). Consequently, limiting NO_2 concentrations at the scrubber inlet is an important consideration. A number of guidance notes (Secretary of State's Guidance, 2004, 2005; European IPPC Bureau, 2006) suggest emission limit values for ammonia from various industrial process ranging from <1 to 5mg/Nm^3 .

An aqueous acid scrubber is expected to be efficient at removing base compounds. However, it is less certain how effective this will be in abating other amine degradation products from the gaseous phase and little data exists on expected abatement efficiencies although some studies (IEAGHGa, 2012/07) suggest that acid wash sections will be effective at removing unwanted amine degradation products. …. scrubbing with acid is reported to be seen as proven and currently state-of-the-art and is being used in some large-scale units (IEAGHG, 2012a). Ammonia emissions of below 5mg/Nm^3 at a pH of 6 were obtained during tests of an acid wash scrubber at TNO's capture plant at Maasvlaakte (Khakharia et al, 2014).


SSE Scope
Shell Scope
Peterhead Power Station
SCR
Steam Turbine
Decarbonized Flue Gas
Capture Plant
Flue Gas
Captured CO_2
Steam
Compression
Oxygen Removal
Installed Interstage
Dehydration Package
New Offshore Pipeline
20"
Existing Offshore Pipeline
20"
Goldeneye Platform
CO_2 Storage


GT Stack
0 mbarg
Flue gas from SSE
Booster fan
90 mbarg
Gas/Gas Exchanger
72 mbarg
Direct Contact Cooler
58 mbarg
Absorber
17 mbarg
-3 mbarg
170m Stack

Battery Limit Conditions (Gas Inlet)	Units	Value Normal Case GT 100%	Value Turn down GT 65% (Note 1)	Value Design Load Max (Note 2)
Ar	vol%	0.90	0.90	0.9
CO	ppmv	0	87	0
total NOx	ppmv	1	1	1
HCl	vol %	0	0	0
HF	vol %	0	0	0
NH_3	ppmv	5	5	5
Dust Load	mg/Nm^3	0	0	0

Notes:

1- A 65% turndown is used for the CCS chain.

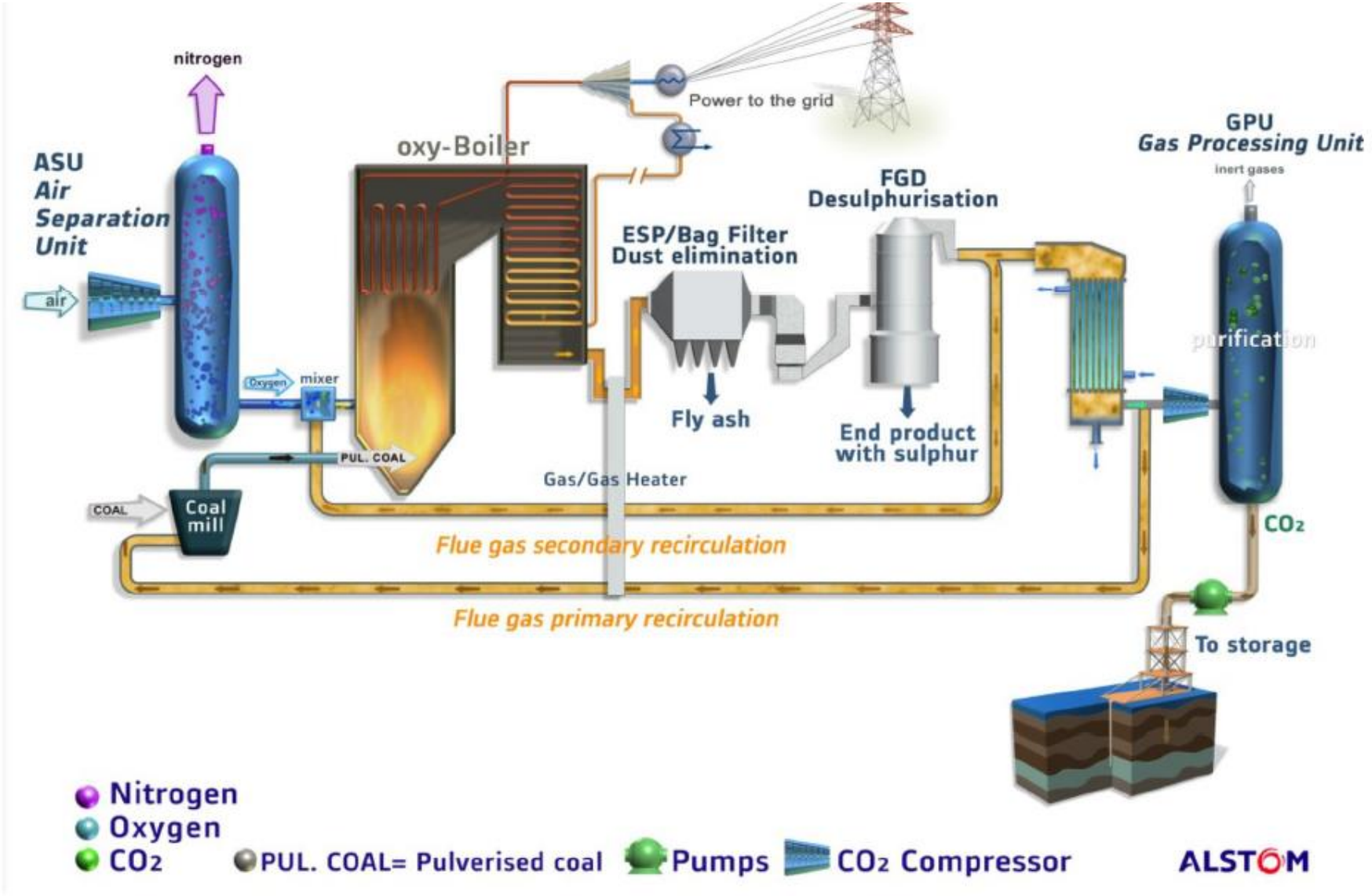
2- Design of pre-treatment unit shall be made for 5 ppmv ammonia but expected value is 2 ppmv.

APPENDIX 3. CCC Documents

	DCC INLET GAS	FLUE GAS TO ABSORBER	TREATED GAS TO STACK
Composition, mol %			
SO_2	0.00014	0.00015	---
CO_2	3.820	3.973	0.422
H_2O	7.700	3.984	4.223
O_2	12.800	13.315	13.694
NH_3	0.00050	0.00008	0.00001
Ar	0.900	0.936	0.006
N_2	74.779	77.791	81.655
NO_2	0.00010	0.00010	---
Total	100.000	100.000	100.000

2. Stream 105 (to stack) contains traces of amines which are not reported in this H&MB.

K27: Oxy Power Plant Process Description



Source: Alstom

K26: Full Chain Effluent Summary

Table 2.1: OPP Stack emissions in oxy mode and air mode

Emissions	Unit	Air-Mode BMCR	Oxy-Mode BMCR
Sulphur Dioxide	g/s	50.830	0.606
Nitrogen Dioxide	g/s	45.830	1.260
Particulates Matter (PM10)	g/s	3.477	0.250
Carbon monoxide	g/s	83.61	15.00
Hydrogen chloride	g/s	1.769	0.001
Hydrogen fluoride (as F)	g/s	0.110	0.001
Arsenic and compounds (as As)	g/s	0.016	0.008
Cadmium and its compounds (as Cd)	g/s	0.001	0.0005
Chromium, chromium(II) compounds and chromium(III) compounds as Cr	g/s	0.007	0.003
Chromium(IV) compounds as Cr	g/s	0.001	0.0005
Copper dusts and mists (as Cu)	g/s	0.007	0.004
Lead	g/s	3.008	0.004
Mercury and compounds, except mercury alkyls (as Hg)	g/s	0.001	0.0001
Nickel (total Ni compounds in PM10 factor)	g/s	0.020	0.009
Selenium and compounds except hydrogen selenide (as Se)	g/s	1.773	0.082
Vanadium	g/s	0.178	0.006
Ammonia	g/s	0.233	0.139

Comparison of SO_2 emission concentrations to emission limits as presented in IED while operating in oxy-mode

Cycle	Units	Cycle 1							
Hour		0 - 1	1 - 2	2 - 3	3 - 4	4 – 5	5 – 6	6 - 7	7 - 8
Sulphur Dioxide (SO_2)	g/s	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Normalised volume flow rate on wet base	Nm^3/h	56440	56440	60822	56490	56440	56440	56440	56440
Emission concentration	mg/Nm^3	38.3	38.3	35.5	38.2	38.3	38.3	38.3	38.3
IED emission limit	mg/Nm^3	150	150	150	150	150	150	150	150
Emission concentration as percentage of IED emission limit	%	26	26	24	25	26	26	26	26
Note: The 24 hour reoccurring process is broken down into three identical cycles therefore emission concentrations have only been presented for the first cycle to provide an indication of concentrations when compared to emission limits specified in the IED.									

One unit operation within the CO_2 capture technology requires cyclical regeneration whereby water vapour is desorbed from a flue gas drier; this is done on an eight hour cycle that produces a time-varying emissions profile.

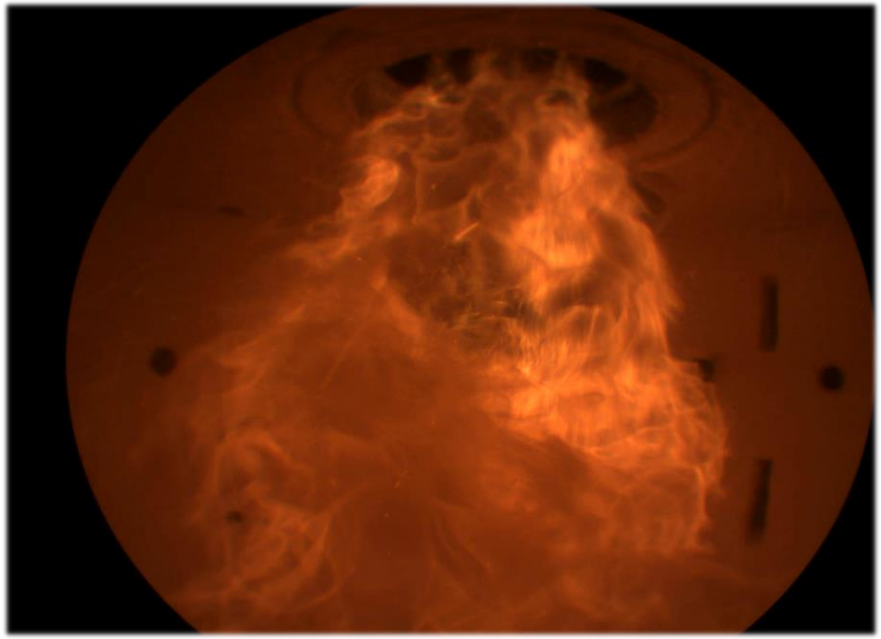
Comparison of NO_x emission concentrations to emission limits as presented in IED while operating in oxy-mode

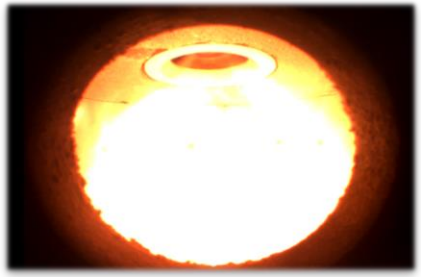
Cycle	Units	Cycle 1							
Hour		0 - 1	1 - 2	2 - 3	3 - 4	4 – 5	5 – 6	6 - 7	7 - 8
Oxides of Nitrogen (NO_x)	g/s	0.920	0.920	3.72	1.01	0.920	0.920	0.920	0.920
Normalised volume flow rate on wet base	Nm^3/h	56440	56440	60822	56490	56440	56440	56440	56440
Emission concentration	mg/Nm3	58.7	58.7	220.2	64.4	58.7	58.7	58.7	58.7
IED emission limit	mg/Nm3	150	150	150	150	150	150	150	150
Emission concentration as percentage of IED emission limit	%	39	39	147	43	39	39	39	39
Note: The 24 hour reoccurring process is broken down into three identical cycles therefore emission concentrations have only been presented for the first cycle to provide an indication of concentrations when compared to emission limits specified in the IED.									

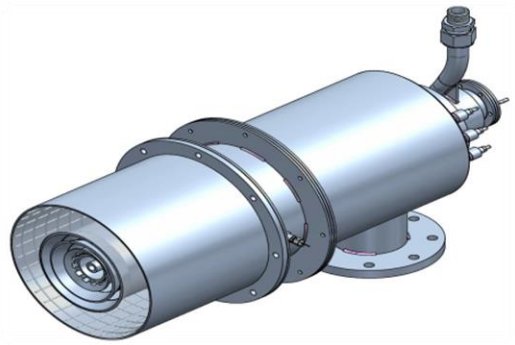
Bio-CAP-UK Project

WP2: PACT Trials (Sheffield)

- Biomass combustion – the biomass burner has been commissioned
- Settings have been optimised – split between primary, secondary (high) and tertiary air and the swirl of each







Bio-CAP-UK Project

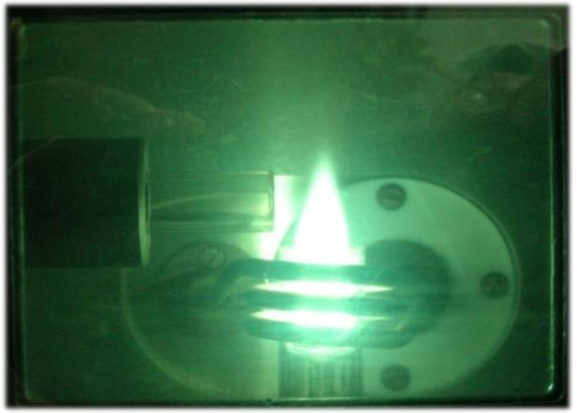
WP2: PACT Trials (Sheffield)

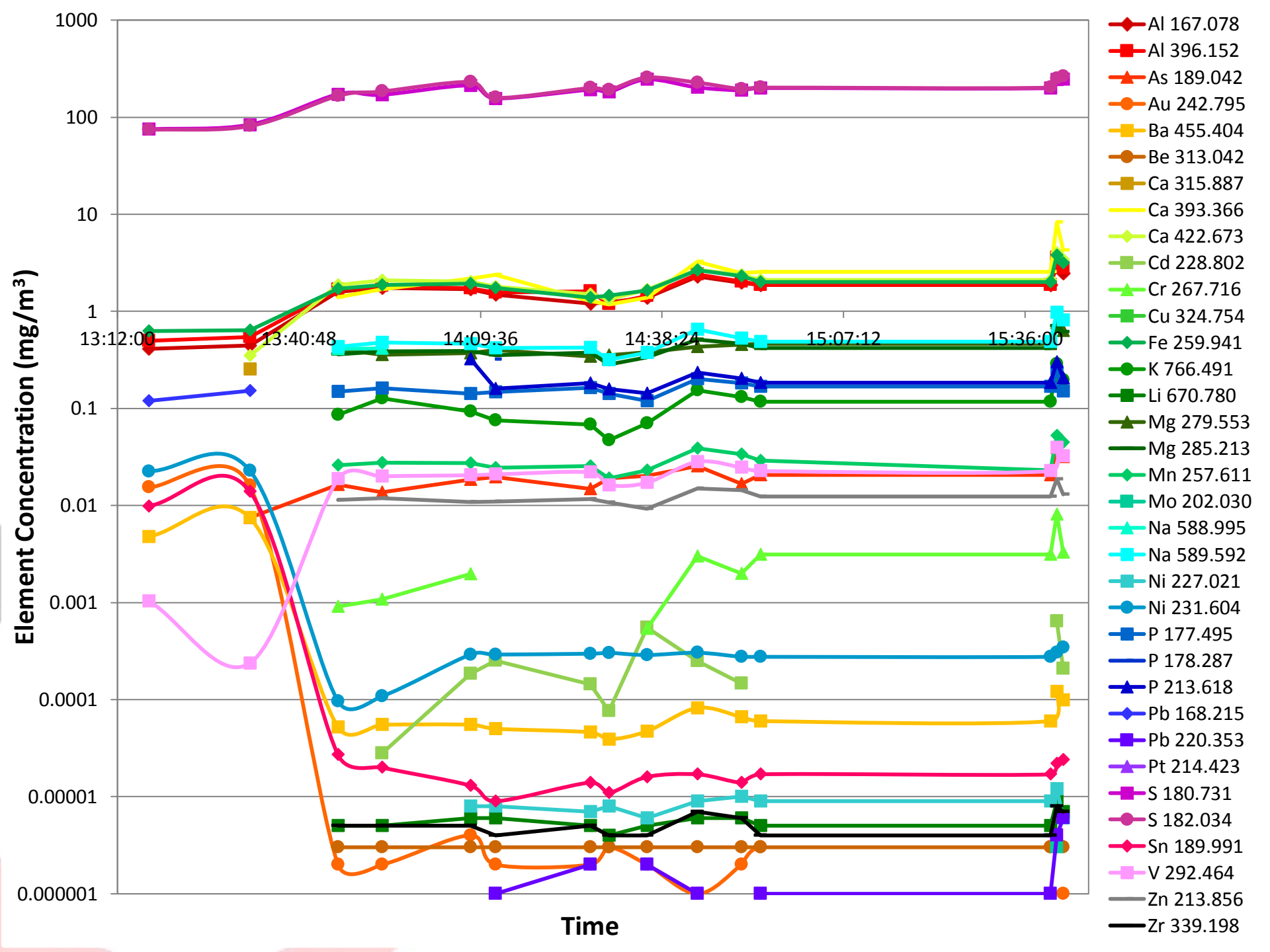
- Impacts of emissions on post-combustion, solvent-based capture
- Use data from ICP (entrained metal aerosols) and DMS (for sub-micron particulate matter)
- Assess the effect of impurities on rates of solvent degradation
  - *focus on elements most likely to impact solvent performance (transition metals that catalyse reactions)*
  - *PM carryover to capture plant*
  - *contamination of the 'pure' CO_2 stream*

Bio-CAP-UK Project

WP2: PACT Trials (Sheffield)

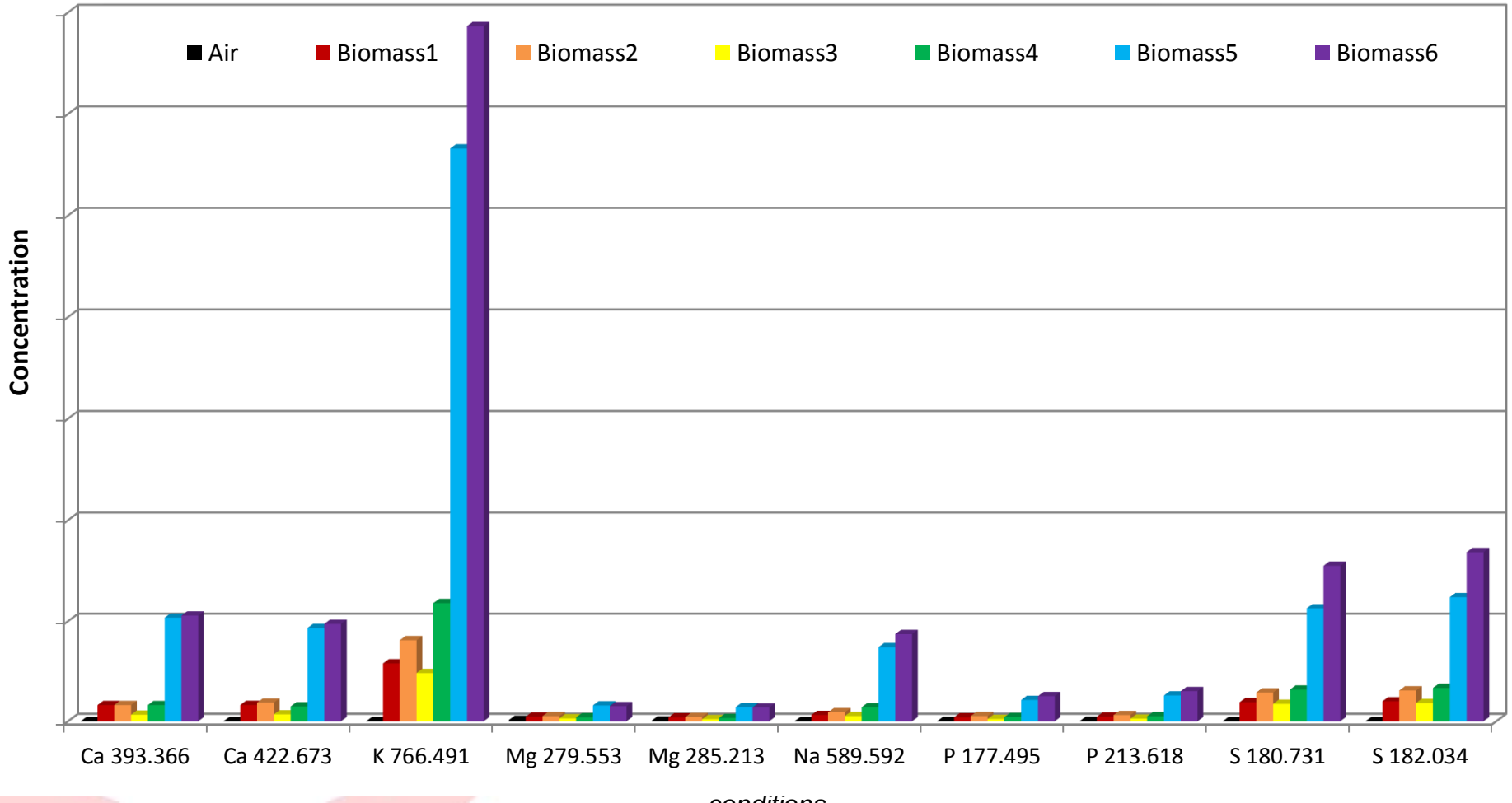
- Continuous, simultaneous multi-elemental detection of entrained aerosol emissions – volatile and non-volatile major to ultra-trace elements using ICP-OES
- Can quantitatively detected in real-time: Al, Au, B, Ba, Br, Ca, **Cd**, Co, **Cr**, **Cu**, **Fe**, **Hg**, I, **K**, Li, Mg, Mn, **Na**, Ni, P, **Pb**, **S**, Sb, Sc, Si, Sn, Th, Ti, **V**, Zn
- Look specifically for elements that cause operational issues, are toxic, easily vaporised and/or found in high concentrations




1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
Element Concentration (mg/m³)
13:12:00
13:40:48
14:09:36
14:38:24
15:07:12
15:36:00
Time
Al 167.078
Al 396.152
As 189.042
Au 242.795
Ba 455.404
Be 313.042
Ca 315.887
Ca 393.366
Ca 422.673
Cd 228.802
Cr 267.716
Cu 324.754
Fe 259.941
K 766.491
Li 670.780
Mg 279.553
Mg 285.213
Mn 257.611
Mo 202.030
Na 588.995
Na 589.592
Ni 227.021
Ni 231.604
P 177.495
P 178.287
P 213.618
Pb 168.215
Pb 220.353
Pt 214.423
S 180.731
S 182.034
Sn 189.991
V 292.464
Zn 213.856
Zr 339.198

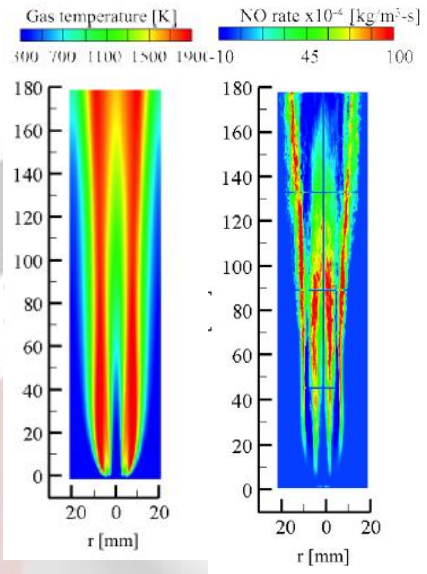
Bio-CAP-UK Project

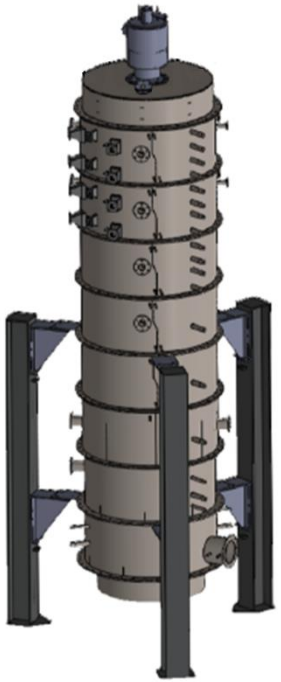
WP2: PACT Trials (Sheffield)

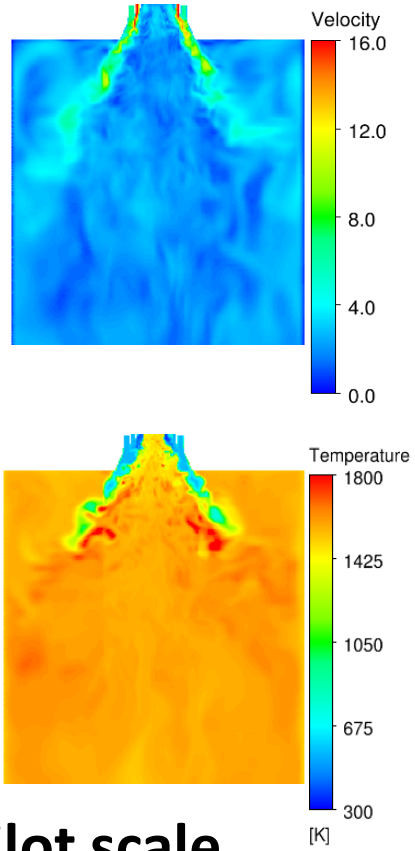


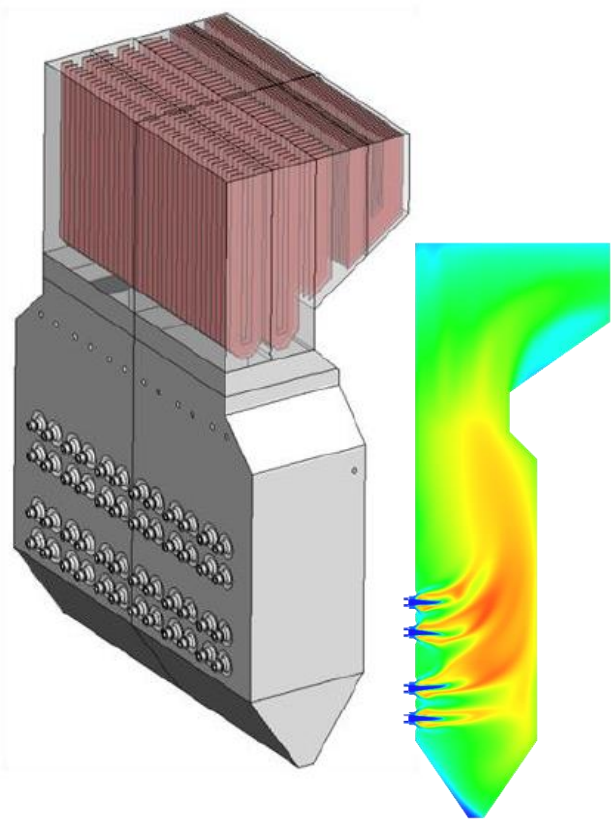
Bio-CAP-UK Project

WP3: Power Plant Simulations (Sheffield/Edinburgh)









Laboratory scale ⟷ Pilot scale (250 kW CTF) ⟷ Full-scale

Conclusions

- Expectation that CCS power plants will have lower ‘conventional’ pollutant emissions than unabated plants.
- Confirmed by recent FEED studies.
- Oxyfuel needs recognition of lower exhaust gas volumes (or vent into N_2 stream from ASU?).
- Post-combustion capture removes conventional pollutants but introduces possibility of degradation products and carryover – but proprietary and major role for wash systems.
- Trace element interaction with post-combustion solvents also important – solvent performance and residue disposal. Biomass introduces new mix of species.