A Global Perspective on the Status of Carbon Capture

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Post Combustion Capture

- Significant progress in reducing energy of regeneration for amine based process
  - Now 2.0-2.3 MJ/Kg CO_2, Cansolv 201 solvent, +others
    - Down from 4-4.5MJ/Kg in 1990
- Significant number of vendors testing or tested at 10MW - 100,000t scale
  - TCM – Cansolv, Aker, Carbon Clean Solutions, ….
  - Shand – Hitachi
  - Shanghai – Huaneng Group
  - Tomakomai – MHI
- Many more at 1-2MW scale - NCC

PCC Developments

Boundary Dam 3, Canada

- Refit of existing coal fired unit
- Operational for 1 year
- CanSolv amine based PCC technology
- 110MWe
- 95% capture
- CO_2 sold for EOR

NRG Parish, USA

- Refit of existing coal fired unit
- Operational in late 2016
- MHI amine based PCC technology
- 250 MW slip stream
- 90% capture
- CO_2 sold for EOR

Post Combustion Capture

- Boundary Dam 3 Operational Achievements
  - March 2016 - a 90% reliability factor had been achieved for the first quarter of 2016
  - July 2016 – 1 millionth tonne of CO_2 had been captured
- Cost reduction from learning by doing
  - 30% CAPEX, 25% OPEX
- A word from the wise!

  "A capture technology must be piloted at a scale that allows for reasonable engineering scale up to a commercial size"

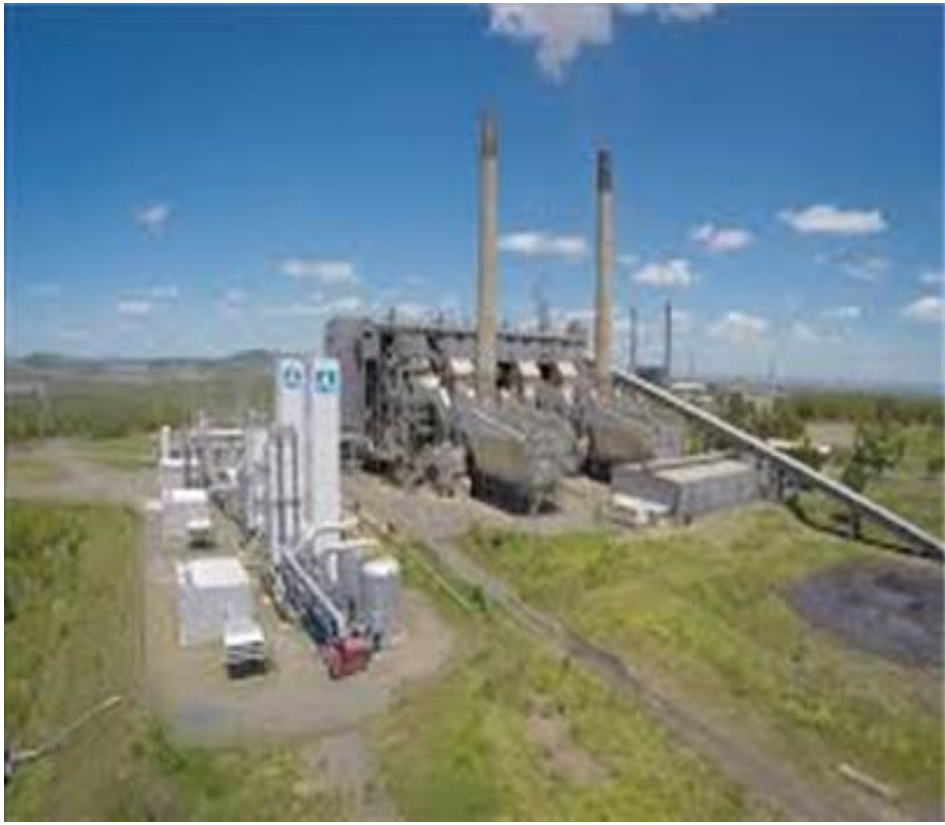
Oxy Combustion

- Alstom/GE
  - 35MWth test facility at Schwarze Pumpe, Germany
  - Engineering design for White Rose 426MWe (gross) – now cancelled
- B&W
  - 30MWth Burner tests, Ohio, USA
  - Engineering design for FutureGen 2.0 159MWe project – now cancelled
- HUST, China
  - 35MWth test facility in Wuhan, China
  - Lead to a 200MWe FEED design

Callide Oxy Fuel Project

Key technical achievements

- 10,200 hours oxy-firing operation and 5,600 hours of CO2 capture plant operation
- A boiler turn-down to 50% Load Factor was demonstrated
- > 95% capture of SOx, NOx, particulates and trace metals
- A high purity of CO2 product (> 99.9%) was produced



"The project was successful and that the technology is ready to move to the full commercial scale."

Supercritical CO_2 Cycles

- IEAGHG techno economic study has evaluated technology options
  - SCOC-CC, S-Graz, NET Power and CES.
- Cycle efficiencies , 49% to 55%
  - NGCC/CCS base case 52% efficiency
- LCOE of base-load plants were 84-95 €/MWh,
- The cost of CO_2 emission avoidance was 68-106 €/t CO_2 avoided.
- The base case was 90% capture
  - Could go to 98% without increasing the cost/t of CO_2 avoided,
  - Or essentially 100% if lower purity CO_2 was acceptable.

Supercritical CO_2 Cycles (2)

Other points

- The cycles could be net producers of water
- Cycles could have advantages at compact sites

Route to commercial deployment

- NET Power is constructing a 50MW power plant
- Toshiba has developed turbine component
- Testing begins in 2017
- If succesful will allow scale up to 295MWe

Pre-combustion capture

- Rectisol and Selexol capture technologies are commercially proven
  - Rectisol process in operation at Dakota Gasification facility since 2000
  - Selexol process to be demonstrated at Kemper County in late 2016
    - No cost overruns on capture component
- Osaki CoolGen Project - IGFC
  - Project is planned in three steps.
    - 166 MW oxygen-blown IGCC to operate in 2017-18
    - Add an amine based capture test facility , 2019 on
    - Add MCFC – 47-49% cycle efficiency

Industry CCS

- CCS now deployed in:
  - Natural gas upgrading – mostly amine based technology (Sleipner, Snohvit, Gorgon …)
    - Game changer – Membrane technology for Lula project, offshore Brazil
  - Hydrogen refining/upgrading
    - Quest – solvent based technology
    - Air Products, PSA technology
  - Steel sector
    - Emirates Steel – Amine based capture

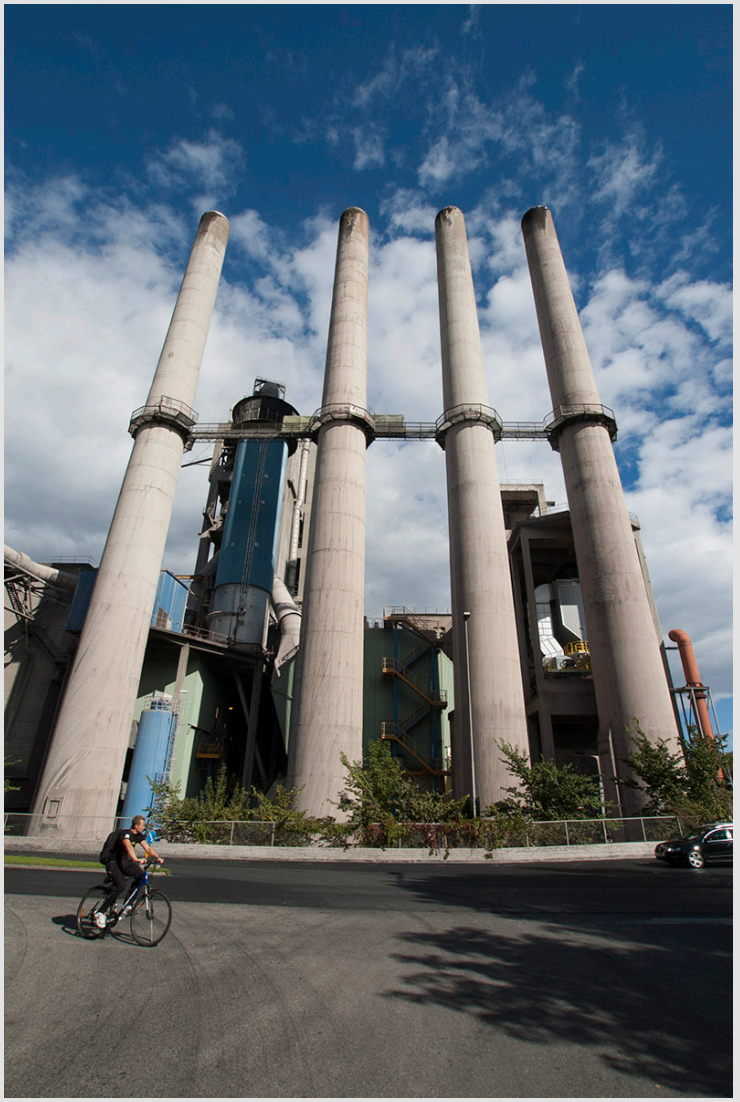
Carbon capture project at Norcem Brevik.

- **CO_2-emissions: 1 mill t/y**
- **CO_2-level in flue gas: 16–20 %**
- **Available excess heat**

- **Funded by**
  - Gassnova through the Climit-program (75%),
  - Norcem / HeidelbergCement
  - ECRA (European Cement Research Academy)

- **Testing 4 technologies**

- **Project period 2013-2017**



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Testing of 4 technologies

Aker Solution

- Liquid amines
- Mobil test-unit (MTU)
- Close to 8000 hours of testing (1,5 year testing)
- Test program completed
- TRL 9

Technology evaluated for full scale application

RTI

- Solid absorption
- Bench-scale-unit in Phase 1
- TRL 5

Next step:

- 3-floor pilot testing (Phase 2) in 2016
- TRL 6?

NTNU/Yodfat/DNV GL

- Membrane-technology
- Bench scale-test
- Stopped after Phase 1
- TRL 5

- New project 2015 - 2016, MemCCC
- Partners: Air Products and NTNU
- Pilot testing 2016!
- Promising technology in the future (2025-2030)
- TRL 6?

Alstom / Univ. in Stuttgart

- Calcium looping
- Lab-scale
- Technology in development
- TRL 3

Technology evaluated to be best suited for a “green field” cement plant

Summary

- Post combustion capture is the technology leader
  - Demonstrated at scale in power sector and industry
  - Cost reduction potential from learning by doing
  - Competitive situation with a large number of vendors, can help drive down costs
- Oxygen combustion technology awaits full scale demonstration, as does IGCC based capture
- Supercritical CO2 cycles show considerable promise
  - Needs to be operationally proven then scaled up
- IGCC/MCFC not on radar at present
- Other novel options are being tested but are not close to the power sector market deployment yet
  - Some niche applications in industry

What Next?

- Next projects on horizon
  - Fluor to demonstrate at ROAD in 2018?
  - Capture at bio-CCS power plant in Japan in 2018?
- Monitor cost reduction and technology developments
  - Which capture options moving up TRL levels?
  - Which options can we get techno-economic estimates on?
    - Chemical looping – 20MW faculty built in France in 2018/19?
- Options and costs of 99-100% capture
  - Higher capture rates important to reduce residual emissions from CCS in future
  - Higher capture process rates or combination with biomass firing?