Post-combustion CO$_2$ Capture at CSIRO
An overview

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Content

- Background
- Pilot plants
- Lab based research projects
- Summary
Coal is important for Australia

- Australia is the world’s largest coal exporter & coal is Australia’s greatest export earner (24.5B$ in 2005-06)
- Most of Australia’s electricity is produced from pulverised coal fired boilers (60% black coal, 20% brown coal)
  - Generation capacity ~ 28 GW
  - Electricity production ~ 170 TWh/a
  - Average generation efficiency
    - Black coal: 35.6% - 0.9 tonne CO₂/MWh
    - Brown coal: 25.7% - 1.3 tonne CO₂/MWh
  - CO₂-emissions ~ 170 Mtonne CO₂/a from ~ 60 flue gas streams
CO$_2$-Capture and Storage: Decarbonisation of fossil fuel chain

- CCS = Capture + Transport + Storage
- CO$_2$-storage least understood, hence main R&D topic
- CO$_2$-transport: Available technologies, but requires infrastructure
- CO$_2$-capture technologies available, but relatively expensive

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Why prefer Post-Combustion Capture?

- Low technology risk
- Flexible operation, in tune with market requirements
- Ability to adopt technology improvements, providing pathway toward zero-emissions
- For new and retrofit applications, preventing stranded assets
Known issues with PCC

- High capture cost
- Electricity cost increase
- Loss of generation efficiency
- Not demonstrated in integrated power plants scale
- Sensitive to O$_2$, SOx and other flue gas constituents
- Large increase in cooling water requirement
Thermodynamic analysis shows a large improvement potential in energy performance of PCC

- **Thermal energy**
  - Regeneration of solvents; Extracted from steam cycle in power plant
- **Electricity**
  - Flue gas fans, Solvent pumps, CO$_2$ compressor

 Derived from Feron, proceedings of GHGT-9, November 2008, Washington
Integrated PCC R&D Programme

Pilot plant programme (Learning by doing)
- Hands-on experience for future operators
- Identification of operational issues and requirements
- Testing of existing and new technologies under real conditions

Lab research programme (Learning by searching)
- Support to pilot plant operation and interpretation of results
- Develop novel solvents and solvent systems which result in lower costs for capture
- Addressing Australian specifics (flue gases, water)
Established Pilot Plants in Australia
General Scope of Pilot Plant Experiments

- Technical and economical scale-up information

- This includes determining the following interrelationships:
  - \( \text{CO}_2 \) capture efficiency and energy consumption
  - Solvent \( \text{CO}_2 \) loading
  - Solvent and flue gas flow rates
  - Regeneration temperature and pressure
  - Absorption temperature
  - Solvent consumption and degradation rates
  - Fouling and corrosion
  - Effectiveness of the conditioning stage
  - Reagent loss rate to acid gas product and slip with flue gas
  - System water consumption
Loy Yang Power Station PCC Pilot Plant
Victoria

- ETIS support
- Lignite
- Amine based
- No FGD/DeNox
- Operational May 08

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Caustic Wash Column

Stripper

Absorber column 1

Absorber column 2

Solvent Feed Tank

Pilot plant scale: 50 kg/h
Design CO₂ capture: 90%
Solvent base: MEA 30%
Commissioning: May 2008
Some results from the Loy Yang pilot plant

- First CO₂ capture in May 2008
- Able to successfully close mass balances over the plant. Agreement between different methods for determining plant CO₂ recovery
- Effect of various operating conditions of plant performance observed (e.g. effect of L/G ratio on CO₂ recovery and reboiler duty

Artanto et. al. 2009
Solvent bench-marking

- MEA has been used as a base case - minimum in pilot: 4.3 MJ/kgCO$_2$

- MEA + AMP and AMP + PZ were used as amine blends and showed decreased heat duty of 10-30%. Kinetics dropped considerably though;

- The RITE solvent, a proprietary amine blend, shows a 20-34% decrease of the heat duty and combines that with seemingly good kinetics;

- Design choices such as packing height, based on MEA properties, has affected the optimal performance of slower reacting, low energy consuming solvents. The brown-coal case demands low investment costs, hence highly reactive solvents;

- Operational issues such as viscosity limits and potential corrosion have limited the impact of results.
Munmorah Power Station PCC Pilot Plant
New South Wales

- APP support
- Black coal
- Aqueous ammonia based
- No FGD/DeNox
- Operational Feb 09
Key Outcomes of the Munmorah Pilot Plant

Benefits of aqueous ammonia process are confirmed …… but further challenges also revealed:

• The ammonia losses, as a result of its high volatility, can be substantial (depending on the operating conditions)
  ▪ necessitates the installation of a comprehensive gas washing and ammonia recovery/neutralisation system.
  ▪ operation at low temperature – refrigeration is expensive to buy and run
• \( \text{CO}_2 \) absorption rates are low
  ▪ larger absorbers compared to the standard amine processes.
  ▪ effect on investment costs?
• Matching operation to regular amine processes
  ▪ formation of ammonium-bicarbonate solids.
  ▪ blockage of the condenser – operational issue
• May still be cost effective multi pollutant process for Australia if we can overcome these challenges with minimal cost
Tarong Power Station PCC Pilot Plant
Queensland, Australia

- APP support
- Black coal
- Amine based
- No FGD/DeNox
- Commissioned November 2010

Australian Government
Department of Resources, Energy and Tourism
Alternative configurations

- Configurations to be tested could be rich split, inter-stage cooling/heating or split flow processes

- Collaboration with University of Texas and URS will enable trials with concentrated piperazine to trial high temperature and pressure regeneration, including two-stage flash regeneration

- Modifications will be tested to provide experimental evidence regarding process modifications to reduce the energy consumption
<table>
<thead>
<tr>
<th></th>
<th>Standard</th>
<th>Intercooling</th>
<th>Split flow</th>
<th>Rich split</th>
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</thead>
<tbody>
<tr>
<td>Reboiler duty</td>
<td>3.75</td>
<td>3.52</td>
<td>3.31</td>
<td>3.36</td>
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<tr>
<td>[MJ/kg CO$_2$]</td>
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<tr>
<td>Cooling duty</td>
<td>4.08</td>
<td>4.11</td>
<td>3.74</td>
<td>3.68</td>
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<tr>
<td>[MJ/kg CO$_2$]</td>
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Validation is pursued through pilot plant and process development facility

Cousins et al., 2011
Novel process development unit

- Located at Newcastle Energy Technology Labs
- Scale between Lab bench scale and Pilot scale
- Modular design
- Flexible operation
- Ventilated & bunded space
- “Controlled” environment
# Pilot plant summary

<table>
<thead>
<tr>
<th>Plant</th>
<th>Loy Yang</th>
<th>Munmorah</th>
<th>Tarong</th>
<th>Newcastle PDF</th>
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</thead>
<tbody>
<tr>
<td>Solvent</td>
<td>Amine</td>
<td>Ammonia</td>
<td>Amine</td>
<td>Both</td>
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<tr>
<td>Flue gas source</td>
<td>brown coal</td>
<td>black coal</td>
<td>black coal</td>
<td>Synthetic</td>
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<tr>
<td>Scale</td>
<td>50 kg/hr</td>
<td>300 kg/hr</td>
<td>100 kg/hr</td>
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<td>Focus</td>
<td>solvent benchmarking</td>
<td>ammonia operation</td>
<td>process optimisation</td>
<td>process development</td>
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<tr>
<td>Other activities</td>
<td>emission study</td>
<td>pressurised absorption</td>
<td>solar thermal integration</td>
<td>cutting edge processes</td>
</tr>
</tbody>
</table>

- Matrix approach helps cover many aspects of PCC as well as providing quicker delivery of information
- Multiple plants provide extra exposure for power generators

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A holistic approach is essential!
Absorbent R&D capability

Speciation in liquid

Absorption rates

Absorbent degradation

Vapour liquid equilibrium
Modelling + Screening of amines
(Puxty et al., 2009)

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Use of Enzymes in PCC

1. Promotion of CO$_2$ capture using enzymes

2. Low energy regeneration of CO$_2$ from amine carbamates using enzymes

Victoria Haritos et al.

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Ionic liquids for PCC

- Standard ionic liquids give low CO$_2$ absorption capacity similar to a physical absorbent
- Functionalised ionic liquids give higher CO$_2$ loadings

- Energy savings up to 70% possible:
  - Absence of water
  - Low heat capacity
  - Low binding energy

- Challenges:
  - High viscosity
  - Low absorption rates
Carbon based sorbents

Design, fabrication, testing and optimization of novel honeycomb monolithic carbon fibre composite adsorbents for CO$_2$ capture

- **Simulated Gases**: Test Gases
  - **Flue Gas**:
    - 10% CO$_2$, 5% O$_2$, N$_2$ balance
    - 10% CO$_2$, N$_2$ Balance
  - **Gas Mixture**:
    - 10%, CO$_2$ 1%, CH$_4$ N$_2$ balance
    - 1% CO$_2$, 5%CH$_4$, N$_2$ balance

- **Operating Conditions**:
  - Flow rates: 0.2 SLM, 0.5 SLM, 1.0 SLM
  - Pressures: atmospheric pressure, 10 bar, 20 bar
  - Temperatures: room

Molding equipment
3 processing furnaces
Fabricated Honeycomb Monolithic Carbon Fibre Composite (CFHM)

Adsorption isotherms (up to 80ºC)
Breakthrough Test Rig with Lab Scale Adsorption Chamber (Length: 200mm, Dia: 35 mm)

Length: 80mm, Dia: 30mm, Number of Channels: 17, Channel Dia: 3mm
Economics of PCC in Australia

Economics and Integration Study

Power plant base case
- Subcritical
- Supercritical Single Reheat
- Ultra-supercritical Single Reheat
- Supercritical Double Reheat
- Ultra-supercritical Double Reheat

STEAM PRO Simulations

ASPN-Plus Simulations

CO₂ capture plant model
- 30% w/w MEA base case

Cost estimates
- PEACE software
- In-house cost data

Integrated plant assessment
- 90% CO₂ capture
- CO₂ capture always on and on demand
- Off-design calculations

STEAM MASTER Simulations

Economic Modelling
Example results from economic modelling

- Supercritical and ultra-supercritical power plants with single reheat provided lowest electricity generation costs
- Example for USC-single reheat and mechanical draft cooling tower

### Power Plant Efficiency
- Power plant efficiency reduced from 40% to 30%
- Electricity generation cost is more than doubled with 90% CO$_2$-capture
- Specific capital costs are doubled with 90% CO$_2$-capture
- Cost per tonne avoided 94 A$/tonne CO$_2$ represents a worst case

### Example results from economic modelling

- **PF Ultrasupercritical single reheat - No Capture**
  - Total Amortised capital cost ($A/MWh)
  - O&M costs excluding fuel ($A/MWh)
  - Fuel cost ($A/MWh)
  - Total Amortised capital cost ($A/MWh) = 46.7
  - O&M costs excluding fuel ($A/MWh) = 9.0
  - Fuel cost ($A/MWh) = 33.0
  - Total Amortised capital cost ($A/MWh) = 776

- **PF Ultrasupercritical single reheat - 90% Capture**
  - Total Amortised capital cost ($A/MWh) = 109.6
  - O&M costs excluding fuel ($A/MWh) = 12.2
  - Fuel cost ($A/MWh) = 68.2

Narendra Dave et al.
Environmental challenges for PCC

- Greenhouse gas emissions reduced
- Addressing gaps in knowledge on additional emissions
- Assessing emission limits of PCC processes
  - Process chemistry
  - Atmospheric chemistry

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- What would be the impact of changing emissions profiles?
Assessment of environmental impacts of PCC

Emission modelling

Transport of pollutants

Smog chamber facility at Lucas Heights

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CSIRO PCC Pilot plant programme is unique in depth and breadth

Liquid absorbent screening of more than 100 candidates has been narrowed down to the 2 most promising candidates (patent application)

Unique position in the application of enzyme technologies and ionic liquids has been realised through patent applications

More IP anticipated in contactors, the regeneration process and designer amines

Excellent insight into the overall economics of PCC has been realised

Establishment of international links with leading groups in the APP region and Europe
Next steps

- First integrated PCC demonstration projects are needed to show the technology works at larger scale.

- Continued need for increasing process efficiency beyond the state-of-the-art, i.e. near-zero emissions and near-zero efficiency loss!

- Continue engagement with stakeholders
  - Power industry
  - Coal industry
  - State governments
  - Federal government

- Increase engagement with technology suppliers
  - CSIRO solvent commercialisation
  - Collaborative development of novel process configurations
CSIRO Energy Technology
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Thank you