Post - Combustion Pathways: Presentation 2

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BCURA, DTI, IEA GHG, TSEC Programme
or

If post-combustion capture is so wonderful how come there isn’t more of it?

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BCURA, DTI, IEA GHG, TSEC Programme
Six rules for effective post-combustion capture

1. Add heat to the steam cycle at as high a temperature as possible (i.e. be prepared to use best available steam conditions if commercially justified).

2. Reject heat from the steam cycle, in the steam extracted for solvent regeneration, at as low a temperature as possible.

3. Produce as much electricity as possible from any additional fuel used, consistent with rejecting heat at the required temperature for solvent regeneration.

4. Make use of waste heat from CO₂ capture and compression in the steam cycle.

5. Use the latest solvent developments.

6. Exploit the inherent flexibility of post-combustion capture.

Gibbins et al, GHGT7
Steam cycle integration

Gibbins et al, GHGT7
# CO₂ Capture as a Factor in Power Station Investment Decisions

Table 1  Comparison of power stations with and without CO₂ capture

<table>
<thead>
<tr>
<th>Technology</th>
<th>Thermal efficiency % LHV</th>
<th>Capital cost $/kW</th>
<th>Electricity cost c/kWh</th>
<th>Cost of CO₂ avoided $/t CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas fired plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No capture</td>
<td>55.6</td>
<td>500</td>
<td>6.2</td>
<td>-</td>
</tr>
<tr>
<td>Post-combustion capture</td>
<td>47.4</td>
<td>870</td>
<td>8.0</td>
<td>58</td>
</tr>
<tr>
<td>Pre-combustion capture</td>
<td>41.5</td>
<td>1180</td>
<td>9.7</td>
<td>112</td>
</tr>
<tr>
<td>Oxy-combustion</td>
<td>44.7</td>
<td>1530</td>
<td>10.0</td>
<td>102</td>
</tr>
<tr>
<td>Coal fired plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No capture</td>
<td>44.0</td>
<td>1410</td>
<td>5.4</td>
<td>-</td>
</tr>
<tr>
<td>Post-combustion capture</td>
<td>34.8</td>
<td>1980</td>
<td>7.5</td>
<td>34</td>
</tr>
<tr>
<td>Pre-combustion capture</td>
<td>31.5</td>
<td>1820</td>
<td>6.9</td>
<td>27</td>
</tr>
<tr>
<td>Oxy-combustion</td>
<td>35.4</td>
<td>2210</td>
<td>7.8</td>
<td>36</td>
</tr>
</tbody>
</table>

Note: The cost of CO₂ emissions avoided for the gas fired plants is relative to the gas fired combined cycle plant without capture. The cost of CO₂ emissions avoided for the coal fired plants is relative to the pulverised coal fired plant without capture.
### Proposed full-scale (~300 MWe and above) CCS projects
*(Based on media reports, press releases and personal communication so indicative only!)*

<table>
<thead>
<tr>
<th>Company/ Project Name</th>
<th>Fuel</th>
<th>Plant output/cost</th>
<th>Capture technology</th>
<th>Start</th>
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</thead>
<tbody>
<tr>
<td>Progressive Energy, Teeside, UK</td>
<td>Coal (petcoke)</td>
<td>800 MW (+ H2 to grid) ($1.5bn)</td>
<td>IGCC + shift + precombustion</td>
<td>2009</td>
</tr>
<tr>
<td>BP/SSE DF1, Peterhead/Miller, Scotland</td>
<td>Natural gas</td>
<td>350 MW, ($600M)</td>
<td>Autothermal reformer + precombustion</td>
<td>2010</td>
</tr>
<tr>
<td>Powerfuel/Kuzbassrazrezugol Hatfield Colliery, UK</td>
<td>Coal</td>
<td>~900 MW</td>
<td>IGCC + shift + precombustion</td>
<td>2010</td>
</tr>
<tr>
<td>BP DF2, Carson, USA</td>
<td>Petcoke</td>
<td>500 MW, ($1bn)</td>
<td>IGCC + shift + precombustion</td>
<td>2011</td>
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<tr>
<td>Statoil/Shell, Draugen, Norway</td>
<td>Natural gas</td>
<td>860 MW</td>
<td>NGCC + Post-combustion amine</td>
<td>2011</td>
</tr>
<tr>
<td>SaskPower, Saskatchewan Canada</td>
<td>Lignite coal</td>
<td>300 MW</td>
<td>PC + Post-combustion or oxyfuel (to be determined Q3 2006)</td>
<td>2011</td>
</tr>
<tr>
<td>E.ON, Killingholme, Lincolnshire coast, UK</td>
<td>Coal (+petcoke?)</td>
<td>450 MW (£1bn)</td>
<td>IGCC + shift + precombustion? (may be capture ready)</td>
<td>2011</td>
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<tr>
<td>Stanwell, Queensland, Australia</td>
<td>Coal</td>
<td>275 MW</td>
<td>IGCC + shift + precombustion</td>
<td>2012</td>
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<tr>
<td>Futuregen, USA</td>
<td>Coal</td>
<td>275 MW</td>
<td>IGCC + shift + precombustion</td>
<td>2012</td>
</tr>
<tr>
<td>RWE, Germany</td>
<td>Coal</td>
<td>450 MW (£1bn)</td>
<td>IGCC + shift + precombustion</td>
<td>2014</td>
</tr>
<tr>
<td>RWE, Tilbury, UK</td>
<td>Coal</td>
<td>~500 MW (£800m)</td>
<td>PC (supercritical retrofit) + post-combustion (may be capture ready)</td>
<td>2016</td>
</tr>
</tbody>
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Jon Gibbins, Imperial College London, Clean Coal: Securing the Future, London 13-14 Sep 2006
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<td>Natural gas</td>
<td>860 MW</td>
<td>NGCC 13 Oct: 300 t/d pilot</td>
<td>2011</td>
</tr>
<tr>
<td><strong>SaskPower, Saskatchewan Canada</strong></td>
<td>Lignite coal</td>
<td>300 MW</td>
<td>PC+ Post-combustion or oxyfuel 30 Oct: Now oxyfuel</td>
<td>2011</td>
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11 Oct: Eon, Kingsnorth, UK  
20 Oct: Conoco-Philips, UK  
26 Oct: International Power, Hazelwood, Australian rumours
Pre Commitment Engineering

<table>
<thead>
<tr>
<th>Year</th>
<th>Plant Definition</th>
<th>Costing</th>
<th>Execution Plan</th>
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</thead>
<tbody>
<tr>
<td>2006</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Engineering**
  - Technology Selection
  - Site Selection

- **Major Contracts**
  - Term Sheets
  - Final Contract
  - Cost/Risk

- **Regulatory**
  - Consultations – Public & Regulatory

- **Project Approvals**
  - Submit EIS
  - Submit Project Recommendation

Ball et al, 5th Ann. Conf. on Carbon Sequestration, 2006
Statoil/Shell 860 MW gas fired power plant, Tjeldbergodden, Norway
Up to 2.5 million tonnes CO₂ injected annually
Describing negotiations between the government and Statoil as "challenging", the Minister of the Environment Helen Bjørnøy says: "We are now presenting an emission permit that secures a full scale CO₂ capture and storage of the cogeneration plant at Mongstad.

In order to reduce technical and financial risk the project will progress in two stages. The first stage, which will be in place when the cogeneration plant starts operation in 2010, will capture at least 100,000 tonnes of CO₂ per year. (~ 300 tpd vs 6,800 tpd)

The second stage, full-scale carbon capture, will be in place by the end of 2014.

Prime Minister Stoltenberg sees the project as an important element in Norway's industrial policy. "We are developing a ground-breaking new technology which can become an export item and a guarantee for a future sector in Norway", he says.

Six rules for effective post-combustion capture

1. Add heat to the steam cycle at as high a temperature as possible (i.e. be prepared to use best available steam conditions if commercially justified).

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5. Use the latest solvent developments.  

6. Exploit the inherent flexibility of post-combustion capture.

Gibbins et al, GHGT7
Secretary of Energy Announces Nearly $24 Million in Grants for Carbon Sequestration Research,
Washington, DC, October 23, 2006

Carbozyme, Inc. : Enzyme-based membrane (x2)
Membrane Technology and Research, Inc. : Membrane-based process, will deliver high-pressure, supercritical CO2 to a pipeline.

University of Akron : Metal monoliths, material synthesis, and low-cost fabrication for CO2 from flue gas.

Praxair, Inc. : Oxygen transport membrane

Research Triangle Institute : Dry, regenerable sorbent

SRI International: Membrane material for pre-combustion-based capture of CO2.

University of Notre Dame: New liquid absorbent

UOP LLC: Microporous metal organic frameworks

ALSTOM to build Pilot Plant in the US to demonstrate its unique CO₂ capture process
05 October 2006

ALSTOM, the Electric Power Research Institute (EPRI) and We Energies are combining forces to build a pilot plant to demonstrate a unique carbon dioxide (CO₂) capture process - a major step in assessing new technology that could have a significant impact on lowering emissions from fossil-fuel-burning power plants.

ALSTOM will design, construct and operate a 5 MW pilot system that will capture CO₂ from a portion of boiler flue gas at the We Energies power plant in Pleasant Prairie, Wisconsin, US.

The pilot is scheduled to be commissioned at the Pleasant Prairie Power Plant in mid-2007 and will be operated for at least one year. EPRI will conduct an engineering/environmental performance and cost analysis during the operation.

http://www.power.alstom.com/pr_power/2006/october/27531.EN.php?languageId=EN&dir=/pr_power/2006/october/&idRubriqueCourante=2727
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Gibbins et al, GHGT7
Efficiency Curves – Supercrit and Subcrit

- Based on net fuel in and power exported
- Heat input of 1285.5 MW$_{th}$ for all 100%MCR cases
- Efficiencies calculated for ‘given’ range of fuel inputs based on base case for that technology

![Graph showing efficiency curves for Supercrit and Subcrit coal with and without capture]

Some early thoughts on potential for amine storage – and how to analyse costs/value?

Diagram:
- **FLUE GAS**
- **CONDENSATE FROM CO2**
- **SOLVENT SOLUTION**
- **CO2**
- **BOILER FEED WATER**
- **COOLING WATER**

**OPTIONAL LEAN SOLVENT STORAGE**

**LEAN/RICH HEAT EXCHANGER**

**GAS TO STACK**

**SCRUBBER**

**REFUX CONDENSERS**

**ALSO REQUIRE POWER FOR CO2 COMPRESSION**

**OPTIONAL RICH SOLVENT STORAGE**

**STripper**

**STEAM FOR CO2 RELEASE**

**REBOILER**

**BLOWER**

**FLUE GAS COOLER**

**CLEANED FLUE GAS FROM POWER PLANT**

**CO2 RELEASE**

**BOILER FEED WATER**

**COOLING WATER**

**SOLENT SOLUTION**

**CONDENSATE FROM CO2**

**FLUE GAS**
Framework for economic analysis using marginal costs?

Price of electricity obtained while solvent is stored determines the adjusted marginal cost of generation when additional solvent is regenerated.

In adjusted costs for regeneration shown here, it is assumed that all solvent is stored during operation at maximum available load (921 MW).

Times are for completing regeneration of additional solvent from storage at given plant output and regeneration rate following one hour of solvent storage at full load.

* Results reported in ECCRIA conference paper – submitted to Fuel
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4. Make use of waste heat from CO₂ capture and compression in the steam cycle.

5. Use the latest solvent developments. Yet another interpretation

6. Exploit the inherent flexibility of post-combustion capture.

Gibbins et al, GHGT7
Guo Yuan and Zhou Dadi,
Low emission options in China’s electric power generation sector,

CHINA: EXAMPLE OF POTENTIAL ‘CARBON LOCK-IN’
kWh From Coal Capacity Forecast AEO’06

Large Proportion of Total Coal-fired kWh From Existing Plants
POSSIBLE CCS TIMING IN KYOTO PHASES

2008-2012  Kyoto Phase 1
• Some early deployment projects

2013-2017?  Kyoto Phase 2
• Greater emphasis on technology
• More widespread CCS development & deployment
• CCS standard on some plants (e.g. coal to liquids)?

• CCS becomes standard in Annex 1 countries?

2023? -?  Kyoto Phase 4
• CCS becomes standard in all countries?
  New build?  Retrofit?
14. We will work to accelerate the development and commercialization of Carbon Capture and Storage technology by:

(a) endorsing the objectives and activities of the Carbon Sequestration Leadership Forum (CSLF), and encouraging the Forum to work with broader civil society and to address the barriers to the public acceptability of CCS technology;

(b) inviting the IEA to work with the CSLF to hold a workshop on short-term opportunities for CCS in the fossil fuel sector, including from Enhanced Oil Recovery and CO₂ removal from natural gas production;

(c) inviting the IEA to work with the CSLF to study definitions, costs, and scope for ‘capture ready’ plant and consider economic incentives; (E.ON, Mitsui Babcock, Imperial IEA GHG project)

(d) collaborating with key developing countries to research options for geological CO₂ storage; and

(e) working with industry and with national and international research programmes and partnerships to explore the potential of CCS technologies, including with developing countries.
GENERAL PRINCIPLES FOR CAPTURE READY

Easy requirements:

a) Space on site and in critical access locations to build CO₂ capture plant and make connections.
b) Design study for adding CO₂ capture.

Challenging requirements:

c) Optional pre-investments to reduce future costs, improve performance etc.

  • Extra/modified equipment
  • Plant siting to reduce storage costs
  • Choice of base plant (PC or IGCC)
<table>
<thead>
<tr>
<th>Plant type (net electrical output approx. 800MW)</th>
<th>Supercrit Pulverised Coal</th>
<th>Supercrit + retrofit postcom</th>
<th>IGCC + retrofit precrom</th>
<th>Supercrit - zero value</th>
<th>New IGCC + precrom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra capital for IGCC w/o capture</td>
<td>£/kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase in specific capital with capture</td>
<td>£/kW</td>
<td>10%</td>
<td>60%</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td><strong>Equivalent plant cost</strong></td>
<td>£/kW</td>
<td>880</td>
<td>968</td>
<td>1408</td>
<td>1258.4</td>
</tr>
<tr>
<td>Capital after depreciation &amp; eff' y loss</td>
<td>£/kW</td>
<td>932</td>
<td>969</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total plant cost for PC retrofit</td>
<td>£/kW</td>
<td>295</td>
<td>103</td>
<td>295</td>
<td></td>
</tr>
<tr>
<td><strong>Capital to repay</strong></td>
<td>£/kW</td>
<td>880</td>
<td>968</td>
<td>1228</td>
<td>1071</td>
</tr>
<tr>
<td>Efficiency (LHV)</td>
<td>% LHV</td>
<td>44.0%</td>
<td>40.0%</td>
<td>34.8%</td>
<td>33.5%</td>
</tr>
<tr>
<td>% CO2 captured</td>
<td></td>
<td>0%</td>
<td>0%</td>
<td>85%</td>
<td>85%</td>
</tr>
<tr>
<td>Fuel cost (LHV)</td>
<td>£/GJ</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
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<tr>
<td>Operating hours</td>
<td>hrs/yr</td>
<td>8000</td>
<td>8000</td>
<td>8000</td>
<td>8000</td>
</tr>
<tr>
<td>Discount rate</td>
<td>%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Plant life</td>
<td>years</td>
<td>25</td>
<td>25</td>
<td>15</td>
<td>15</td>
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<tr>
<td>CO2 storage cost (aquifer/gas field)</td>
<td>£/tonne CO2</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
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<tr>
<td><strong>Cost of electricity</strong></td>
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<td></td>
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<tr>
<td>Capital</td>
<td>p/kWh</td>
<td>1.21</td>
<td>1.33</td>
<td>2.02</td>
<td>1.76</td>
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<tr>
<td>Operating expenditure</td>
<td>p/kWh</td>
<td>0.38</td>
<td>0.38</td>
<td>0.56</td>
<td>0.44</td>
</tr>
<tr>
<td>Fuel</td>
<td>p/kWh</td>
<td>1.15</td>
<td>1.26</td>
<td>1.45</td>
<td>1.50</td>
</tr>
<tr>
<td>CO2 storage costs</td>
<td>p/kWh</td>
<td>0.00</td>
<td>0.00</td>
<td>0.44</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Cost of electricity ex. EU ETS</strong></td>
<td>p/kWh</td>
<td>2.73</td>
<td>2.97</td>
<td>4.46</td>
<td>4.16</td>
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<tr>
<td>Emission allowance costs</td>
<td>p/kWh</td>
<td>1.85</td>
<td>2.03</td>
<td>0.35</td>
<td>0.36</td>
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<tr>
<td><strong>Cost of electricity inc. EU ETS</strong></td>
<td>p/kWh</td>
<td>4.58</td>
<td>5.00</td>
<td>4.82</td>
<td>4.52</td>
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<tr>
<td><strong>Marginal cost of generation</strong></td>
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<td>0.45</td>
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<tr>
<td>Variable OPEX</td>
<td>p/kWh</td>
<td>0.19</td>
<td>0.19</td>
<td>0.28</td>
<td>0.22</td>
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<td>3.48</td>
<td>2.52</td>
<td>2.54</td>
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Some capture-ready steam turbine options
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6. Exploit the inherent flexibility of post-

Yet more interpretations possible (e.g. variable capture levels, post-com on other processes)

Gibbins et al, GHGT7
**Conclusions**

- Flexibility is a good thing (really)
- But it makes life very complicated sometimes
- Post-combustion >> Amine
- Killer application #1 for post-com capture on coal retrofit? (capture-ready plants)
- Killer application #2 variable output? (can’t all be base-load)
- The global climate-change consensus that would justify retrofits is not there, yet
- We need to be ready if/when it is
Coal Capacity History and Forecast AEO’05

1973 additions greater than total for last 15 years

Will the Nation’s Industry be Prepared and Capable of Meeting This Coal Plant Forecast?

NETL

Forecast - Annual Energy Outlook 2005
Historic Data - UDI 2001 Operating Data

June 20, 2005
30 Oct

There is still time to avoid the worst impacts of climate change, if we take strong action now.

www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm
There is a strong case for greater international co-ordination of programmes to demonstrate carbon capture and storage technologies, and for international agreement on deployment.

Building on these announcements, the enhanced co-ordination of national efforts could allow governments to allocate support to the demonstration of a range of different projects, and demonstration of different pre and post combustion carbon capture techniques from different generation plants, since the appropriate technology may vary according to local circumstances and fuel prices.

One element that enhanced co-ordination could focus on is understanding the best way to make new plants “capture-ready”, by building them in such a way that retrofitting CCS equipment is possible at a later date.