Squaring the Circle on Coal - Carbon Capture and Storage (CCS)

Claverton Group conference, Bath 24-26 October 2008

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Research Associate, Process Technology Group, Dept of Engineering Science, Oxford University
How CCS works
“The field of carbon capture and storage is a long-term priority for the European Commission and the sector as a whole”

IEA, Stern review, EU, IPCC all state that “CCS is a key measure to meet 2030, 2050 CO2 targets – expect to provide ~30% of all CO2 reductions from power industry”

2030 = 500-550 plants (EU 80-120) saving 3.6 GT/y of CO2
EU ‘CASTOR’ post-capture small pilot plant startup, Mar 2006

Europe Tests Carbon Capture at Coal-Fired Power Plant

ESBJERG, Denmark, March 15, 2006 (ENS) - The world’s largest pilot plant for the capture of carbon dioxide (CO2) from a conventional power station was opened in Denmark today. It is the first installation in the world to capture the CO2 in the flue gases of a coal-fired power station.

The pilot project at the Elsam power station near Esbjerg, will demonstrate new technology for capturing carbon dioxide emissions as they are produced by power stations and then storing the CO2 emissions underground, so they cannot enter the atmosphere and produce the greenhouse effect responsible for global warming.

Elsam coal-fired power plant at Esbjerg, Denmark is the site of the CASTOR pilot project. (Photo courtesy Elsam)

CASTOR, which stands for CO2 from Capture to Storage, is an European initiative grouping 30 partner industries, research institutes and universities from 11 European countries.

“The European Commission is committed to a low-carbon future, said European Science and Research Commissioner Janez Potocnik, commenting on the inauguration of the new pilot plant at the 420 megawatt Elsam power station.
Kårstø CCGT CCS Project, Norway

The Norwegian Government will construct a full scale CCS (retrofit) solution for a gas-fired power plant in connection to the existing gas fired power plant at Kårstø on the Western coast of Norway. The capture plant is planned to be operational as soon as possible. The plan is to make the investment decision in 2009. The facility is planned to capture 1 million tonnes/year of CO2 from the exhaust gas at the power plant and subsequently transport the CO2 by pipeline to safe storage in geological formations under the sea bed. The State owned entity Gassnova is responsible for this important and comprehensive work. The investment cost would amount to approximately 5 billions NOK, including transport and storage of CO2. Abatement cost (NPV) of NOK 700 per ton CO2.
World primary energy consumption slowed in 2007, but growth of 2.4% was still above the 10-year average. Coal remained the fastest-growing fuel, but oil consumption grew slowly. Oil is still the world’s leading fuel, but has lost global market share for six consecutive years, while coal has gained market share for six years.
World coal consumption grew by 4.5%, well above the 10-year average. Coal was the world’s fastest-growing fuel for the fifth consecutive year. Growth was above average in all regions except the Middle East. Chinese consumption growth accounted for more than two-thirds of global growth.
<table>
<thead>
<tr>
<th>Attribute</th>
<th>Coal</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability/continuity</td>
<td>Very high</td>
<td>Very low</td>
</tr>
<tr>
<td>Predictability</td>
<td>Very high</td>
<td>Very low</td>
</tr>
<tr>
<td>Outages</td>
<td>Plannable</td>
<td>Unplanned</td>
</tr>
<tr>
<td>Ability to back-up other plant on-demand</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Spinning-reserve ability</td>
<td>Yes (good)</td>
<td>No</td>
</tr>
<tr>
<td>Land area per MW</td>
<td>v. small</td>
<td>v. large</td>
</tr>
<tr>
<td>Retrofit to existing sites/grid</td>
<td>Yes (near-100%)</td>
<td>Tiny</td>
</tr>
<tr>
<td>Planning consent</td>
<td>Accepted</td>
<td>Controversial (onshore)</td>
</tr>
<tr>
<td>Need for new grid lines</td>
<td>Minimal</td>
<td>Significant</td>
</tr>
<tr>
<td>Fuel storage</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Fuel storage cost</td>
<td>Low</td>
<td>N/A</td>
</tr>
<tr>
<td>Expected energy-source price rise</td>
<td>Moderate</td>
<td>Zero</td>
</tr>
<tr>
<td>Capital cost/MW</td>
<td>Moderate</td>
<td>v. high</td>
</tr>
<tr>
<td>Power cost/MWh</td>
<td>Below grid average</td>
<td>High</td>
</tr>
<tr>
<td>Need for subsidy</td>
<td>Zero (no CCS)</td>
<td>Moderate (CCS)</td>
</tr>
<tr>
<td>Competitiveness vs. gas CCGT</td>
<td>Improving</td>
<td>Improving</td>
</tr>
</tbody>
</table>
Plant decision process:

- 1) CEGB/Gov’t (1985)

‘Fuel’

Lifetime cost

Avoiding imports

Security

Operational factors

Capital cost

(Gov’t, g’teed, 6% interest)
Plant decision process:
- 2) Privatised (today)

- Lifetime cost
  (NPV at 10% DCF)
- ‘Fuel’ (10% DCF) security
- Operational factors
  (Avoided CAPEX of backup)
- Avoiding imports
- Capital cost
  Commercial bank
  (Interest 12%)
CO2 capture unit

Treated flue gas

Absorber

CO2 rich solvent

Exchanger

CO2-poor solvent

Regenerator

Flue gas to be treated

CO2 to storage

Energy
## CO2 capture process options
(all the processes down to Benfield HiPure are fully proven with guarantees)

<table>
<thead>
<tr>
<th>Physical solvents</th>
<th>Chemical solvents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Amines:</td>
</tr>
<tr>
<td>Selexol</td>
<td>MEA</td>
</tr>
<tr>
<td>Rectisol (methanol)</td>
<td>DEA</td>
</tr>
<tr>
<td>Purisol</td>
<td>MDEA</td>
</tr>
<tr>
<td>Fluor Solvent</td>
<td>DGA</td>
</tr>
<tr>
<td></td>
<td>Fluor Econamine</td>
</tr>
<tr>
<td><strong>Hybrid</strong></td>
<td><strong>Carbonates:</strong></td>
</tr>
<tr>
<td>Sulfinol</td>
<td>Benfield</td>
</tr>
<tr>
<td>ADIP</td>
<td>Vetrocoke</td>
</tr>
<tr>
<td>Flexsorb</td>
<td>Hybrid:</td>
</tr>
<tr>
<td></td>
<td>Benfield HiPure</td>
</tr>
<tr>
<td><strong>Novel:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alstom ammonia</td>
</tr>
<tr>
<td></td>
<td>Cansolv</td>
</tr>
</tbody>
</table>
How CCS works - technologies

**PRE COMBUSTION**

- OXY-FUEL
- CO₂ separation
- CO₂ compression and dehydration

**POST COMBUSTION**

- Technologies
- Flue gas
- Power & heat
- CO₂ separation
- H₂
- Gas, ammonia, steel etc

**INDUSTRIAL PROCESSES**

- Gasification
- Reforming / CO₂ separation
- Power & heat
- CO₂ compression and dehydration

- Air separation
- Power & heat

- Gasification
- Reforming / CO₂ separation
- Power & heat
- Gas, ammonia, steel etc

**Air separation**

- Gasification
- Reforming / CO₂ separation
- Power & heat
- Gas, ammonia, steel etc

**Fuel**

- Gas / oil
- Air
- Raw materials

**Air**

- Air / O₂ / steam
- Fuel
- Air
Gasifier Market

• Total (inc. construction/planned):
  • 163 sites with 450 gasifiers
  • SASOL’s 3 sites in S. Africa alone have 97 Lurgi fixed-bed coal gasifiers + US Great Plains SNG demo plant has another 14
  • 140 sites already in operation
  • Coal – 37 sites Oil Residues, biomass etc – 126
  • 115 sites – chemical syngas + a few pipeline gas
  • 48 IGCC sites – 16 operating, 32 planned
  • Operating IGCC:
    • Coal-6, Oil residues-7, small biomass -3
WORLD SYNGAS CAPACITY GROWTH
(MEGAWATTS THERMAL EQUIVALENT)

Source: Gasification Technologies Council
PRODUCT DISTRIBUTION OF 2007 WORLD GASIFICATION CAPACITY

- 30% LIQUID FUEL
- 19% POWER
- 45% CHEMICALS
- 6% GASEOUS FUEL

GLOBAL SYNGAS OUTPUT BY FEEDSTOCK

- 55% COAL
- 32% PETROLEUM
- 8% GAS
- 3% PETCOKE
- 2% BIOMASS/WASTE
Refinery gasification market opportunity

- Refinery
- Gasif’N
- Resid.
- Steam
- Fuel Oil
- Power
- Power Plant
- Owned by Others
- NO TAX
- TAX
Refinery Gasification

• Operation within the refinery:
• Saves refining the residues to fuel oil specification
• Flexibility in feedstock – any waste oils/gases – helps refinery balance
• Supplies the refinery power, steam and heat “at-cost”
• Avoids fuel oil tax
• Can use refinery support services (water, effluent treat, etc)
Biomass+waste IGCC Plants (non-CCS)

<table>
<thead>
<tr>
<th>Location</th>
<th>Country</th>
<th>Technology</th>
<th>Capacity</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schwarze Pumpe</td>
<td>Germany</td>
<td>BGL (chemicals)</td>
<td>37MW</td>
<td>1995</td>
</tr>
<tr>
<td>Americentrale</td>
<td>Holland</td>
<td>Lurgi CFB</td>
<td>46MW</td>
<td>2000</td>
</tr>
<tr>
<td>Kymijarvi</td>
<td>Finland</td>
<td>FW CFB</td>
<td>26MW</td>
<td>1998</td>
</tr>
<tr>
<td>Varnamo</td>
<td>Sweden</td>
<td>FW CFB</td>
<td>6MW</td>
<td>1993</td>
</tr>
<tr>
<td>Renovavel</td>
<td>Brazil</td>
<td>TPS</td>
<td>37MW</td>
<td>2005</td>
</tr>
</tbody>
</table>

Biomass and waste gasify **easier** than coal (more reactive)
Waste “gate fees” -> lower power cost
Biomass/waste IGCC +CCS = **NEGATIVE** CO2 emission!!
### Some IGCC Prototype Plants

<table>
<thead>
<tr>
<th>Plant</th>
<th>Country</th>
<th>Developer</th>
<th>Capacity (MW)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool Water*</td>
<td>USA</td>
<td>CVX(Texaco)</td>
<td>100</td>
<td>1984</td>
</tr>
<tr>
<td>Wabash River</td>
<td>USA</td>
<td>E-Gas (Destec)</td>
<td>262</td>
<td>1995</td>
</tr>
<tr>
<td>Polk (Tampa)</td>
<td>USA</td>
<td>CVX(Texaco)</td>
<td>250</td>
<td>1996</td>
</tr>
<tr>
<td>Pinon Pine*</td>
<td>USA</td>
<td>KRW (air)</td>
<td>107</td>
<td>1996</td>
</tr>
<tr>
<td>Buggenum</td>
<td>Holland</td>
<td>Shell SCGP</td>
<td>253</td>
<td>1995</td>
</tr>
<tr>
<td>Puertollano</td>
<td>Portugal</td>
<td>Prenflo</td>
<td>300</td>
<td>1997</td>
</tr>
<tr>
<td>Delaware</td>
<td>USA</td>
<td>CVX(Texaco)</td>
<td>284</td>
<td>2001</td>
</tr>
<tr>
<td>Sulcis</td>
<td>Sardinia</td>
<td>Shell SCGP</td>
<td>522</td>
<td>2005</td>
</tr>
</tbody>
</table>

* - shut down
IGCC Process

Alternatives:
- Asphalt
- Coal
- Heavy Oil
- Petroleum Coke
- Crumulsion
- Natural Gas
- Wastes

Power Block

Gasification Block

Gasifier

Oxygen

Syngas

Sulfur Removal

Marketable Byproducts:
- Sulfur

Slag

Alternatives:
- Hydrogen
- Ammonia
- Chemicals
- Methanol
- Fischer-Tropsch Liquids (zero sulfur diesel)

Source: GE  Basis: Texaco (CVX) gasifier
2. Outline of Negishi IGCC

Process Block Diagram

- Gasifier Scrubber LTGC
- ASU
- HRSG
- GT
- ST
- TEPCO
- Stack
- Steam
- Syngas
- O2
- N2
- Black Water
- Gray Water
- NH3 Water
- WWT
- SWS
- SRU
- AGE
- TGT
- Sulfur
- Incinerator
- Healthy Water
- Sea
Gasification as a Solid Fuels Purifier

• Removal of:
  – Ash (solids)
  – Sulphur
  – Nitrogen (ammonia)
  – Chlorine/fluorine
  – Trace heavy metals (Ni,V,Pb….)
  – Trace alkali metals (Na,K,…)
  – Organic compounds
  – Carbon as CO2
Flow Directions

- **GAS**
  - **SOLIDS**

**FIXED BED**
- COUNTER-CURRENT
  - (4 types)

**FLUIDISED BED**
- CROSS-FLOW
  - WELL-STIRRED
  - (3 types)

**ENTRAINED**
- UP-FLOW
  - CO-CURRENT
  - (3 types)

- DOWN-FLOW
  - CO-CURRENT
  - (3 types)

ASH
Figure 5.2 The British Gas Lurgi Gasifier (White 2000)
Figure 5.3 Schematic of IGCC showing key system components
Negishi 431MW Residue Oil IGCC plant

- Oxygen plant
- Combined Cycle
- Gas purif’n
- Gasifier plant
CVX (Texaco) gasifier tower, Polk 250MW IGCC plant, Tampa, Florida
Bellingham, USA – GT powerplant - CO2 absorber unit

Fluor absorber in USA for 360 tonne/day CO₂
Bellingham, USA – GT powerplant - CO2 absorber unit
Large amine absorber, Saudi Arabia refinery

Fluor’s Econamine (DGA) Plant in Uthamaniyah, Saudi Arabia has an absorber (center-right) with a large diameter.
Great Plains (aka Dakota Gasification) SNG Plant CCS project, Beulah, North Dakota, USA – “is this proven enough for you”? (153 million ft³/day CO₂ pipelined and sequestered, 160 million ft³/day SNG produced to pipeline) - 13 MT sequestered so far
Enhanced Oil Recovery in North Dakota / USA
CO2-Compressor of an Integrally Geared Design

Project description
In 1997 MAN TURBO received an order for a compressor high pressure application. The compressor station consists of two units to feed CO2 in the front end station of a pipeline starting in a coal gasification plant in North Dakota, USA. The pipeline routes from North Dakota over the canadian boarder to Saskatchewan oil fields, where the CO2 is injected into oil wells for enhanced oil recovery. The total length of this 14 inch pipeline is 205 miles. There are no booster stations foreseen in between. The CO2 gas is injected into the oil well directly out of the pipeline, which requires a high pressure at start.

Source: MAN Turbo website

MAN CO2 Compressor – 10 stages, 125 tonnes/h, 190 bar pressure
Great Plains SNG plant - EOR CO2 international pipeline map (205 miles)
Why is Purification Easier for IGCC? – pre-combustion purification

PC + post-capture
P = 1 atm

IGCC + pre-capture
30 atm

M = Molar flow (relative)  V = actual volume flow
Why is Purification Easier? – 2

• Conv. Powerplant:
  – 180x Volume flow – huge equipment
  – Contaminants in oxidised form (SO2, NOx, CL2) – less soluble + attacks Amines (also resid. O2)
  – Pressure = 1 atm -> tiny driving forces for absorption
    -> v. large absorbers

• IGCC:
  – Vastly lower volume flow
  – Contaminants in reduced form (H2S, NH3, HCL) – more soluble, no problems
  – Pressure = 20-50 atm -> large partial-pressure driving forces for absorption
    • Can use physical solvents (<< lower energy use)
  – Conventional absorption process equipment
Why is Purification Easier? –3

• Conv. Powerplant:
  – Treated gas required dry and at >85 C for chimney plume rise
    • High temp. -> low absorption driving force
    • >60% of ash in flue gas as fine dust
    • Dry dust removal difficult - Electrostatic Precipitators (ESP)
    • High inherent NOX formation from direct coal combustion

• IGCC:
  – Gas turbine accepts fuel gas wet and at 15-40C
  – Gas cooling energy loss low because small flow
  – Ash dust in gas can be <10% for some gasifiers
  – Wet dust removal easy/ “natural”
  – lower inherent NOX formation + low-Nox burners for fuel gas
  – Easier NOx removal options (dust-free gas)
Purification - results

• Conv. Powerplant:
  – All Sulphur (SO2) removal expensive
  – Sulphur (SO2) removal >90% difficult
  – Dust removal >98% difficult
  – NOx reduction/removal to <500 ppmv difficult/costly
  – Post-combustion CCS very costly

• IGCC:
  – >99% removal of all non-CO2 impurities affordable
  – CO2: 90% removal affordable, 99.999% practicable
  – Typically down to few-ppmv* level
  – Sulphur +nitrogen +ash all recovered as saleable products
  – NOx reduction to 25 ppmv “routine”
  – NOX removal to 3 ppmv achievable at moderate cost (burners)
  – BUT: ‘difficult’ liquid chemical effluents
Purification - Conclusion

- IGCC will steadily become a more desirable option as environmental regulations tighten, putting up the cost of conventional solid fuel powerplant (PC) as clean-up systems are added
## Current Options

<table>
<thead>
<tr>
<th></th>
<th>IGCC</th>
<th>SCPC</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost</td>
<td>$/kW</td>
<td>$1,450</td>
<td>$1,225</td>
</tr>
<tr>
<td>Emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- NOₓ</td>
<td>lb/MMBtu</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>- SO₂</td>
<td>lb/MMBtu</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>- PM</td>
<td>lb/MMBtu</td>
<td>0.005</td>
<td>0.01</td>
</tr>
<tr>
<td>Efficiency</td>
<td>% HHV</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Fuel Flexibility</td>
<td>Feedstocks</td>
<td>All coals plus liq. &amp; solid opportunity fuels</td>
<td>Low sulfur coals favored</td>
</tr>
<tr>
<td>COE (1st year)</td>
<td>$/kWh</td>
<td>4.22</td>
<td>3.94</td>
</tr>
</tbody>
</table>

Source: GE      Basis: Texaco (CVX) gasifier
IGCC Is a Pollution Prevention Solution Capable of Meeting Future Environmental Challenges

<table>
<thead>
<tr>
<th></th>
<th>IGCC</th>
<th>SCPC</th>
<th>Concerns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>Removal %</td>
<td>95%</td>
<td>40%-70%</td>
</tr>
<tr>
<td></td>
<td>$/lb</td>
<td>$3,412</td>
<td>$37,800</td>
</tr>
<tr>
<td>Water</td>
<td>gal/MW-hr</td>
<td>304</td>
<td>521</td>
</tr>
<tr>
<td>CO₂</td>
<td>kW penalty</td>
<td>-5%</td>
<td>-28%</td>
</tr>
<tr>
<td></td>
<td>Capital Cost</td>
<td>+30%</td>
<td>+73%</td>
</tr>
<tr>
<td></td>
<td>COE Increase</td>
<td>+25%</td>
<td>+66%</td>
</tr>
<tr>
<td>Solid Waste</td>
<td>COE, c/kWhr</td>
<td>5.25</td>
<td>6.54</td>
</tr>
<tr>
<td>Sludge</td>
<td>lb/MW-hr</td>
<td>0</td>
<td>156</td>
</tr>
<tr>
<td>Ash</td>
<td>lb/MW-hr</td>
<td>0</td>
<td>71</td>
</tr>
<tr>
<td>Aggregate</td>
<td>lb/MW-hr</td>
<td>71</td>
<td>0</td>
</tr>
<tr>
<td>(vitrified)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: GE      Basis: Texaco (CVX) gasifier
IGCC - The problems

- IGCC has:
  - ~20% higher capital cost than PC at present (non-CCS)
  - Higher plant complexity
  - Requires skilled process engineers
  - 20-30% energy loss in gasification/purification stage; combined cycle has to be very efficient to balance this
  - Needs oxygen separation plant – high cost, high power use, O2 hazardous
  - “difficult” liquid effluents (-but much lower flow)
  - High temperature corrosion issues
  - Less proven technology (improving)
  - Fewer manufacturers
IGCC- The Opportunities

• Benefits “for free” from GT efficiency + size developments for normal NG CCGT
• Benefits from improved novel CCGT cycle designs
• More compact, road/rail-portable process equipment, of standard types for process industry contractors
• Opportunities for better energy integration with GT, oxygen plant
• Potential improved gas purification methods, e.g. “hot/dry” treatment
• Cost reduction “learning curve”
• Economies of scale for larger units
IGCC- The advantage for CCS

- a decisively lower CCS penalty compared with post-capture on both power de-rating (5 vs 28%) and power cost increase (25% vs 66%)

- this makes IGCC + pre-capture the definitive economic choice in a full-CCS new-build scenario
CARBON CAPTURE & COMPRESSION COSTS*
(DOLLARS PER METRIC TON)

*Mark Costa 2007 BTO Presentation
Source: MIT and Eastman Chemical Company
CCS cost – McKinsey report Sept 08

- IEA Forecast:
  - Total global power use +100% (x 2) in 2030
  - Fossils share **INCREASES** to 70%

2030 cost: €35-50 /t CO2 saved

  = **PARITY** with expected ETS price

- 1st demo’s cost: €60-90 /t CO2 saved

- Cost 90% capture, 5% transport, 5% storage

- BASIS: 900MW plant, supercritical 50% effy “pre-CCS”, 86% availability/CF *(NO CCS penalty)*, CCS eff’y penalty 7-12 “% points” (14-24% extra fuel), **ZERO*** EOR credit, 40 year life, hard coal €65/T, transp’+store 100km/onshore <-> 200km/offshore

- **Extra** 200km transp’ adds only €10/T
How CCS works
How CCS works - storage options
Enhanced Oil Recovery (EOR) process

oil producing well  gas injection well

oil  gas

oil
Storage sites

Oil fields
Gas fields
Gas/condensate fields
Saline-water-bearing reservoir rocks (saline aquifers)
Coal seams

(Courtesy BGS)
CO2 disposal pipeline network
Proposed UK CCS Sites
(map source: The Association of British Counties)
Oxygen-steam gasifiers-1

• Fixed-bed
  − Producers (P = 1 atm)
  − Lurgi
  − GSP (Lurgi copy)
  − BGL (slagging)
  − BGL Composite (hybrid fixed/entrained)

• Fluidised bed
  − HTW (High-Temperature Winkler)
  − KRW (Kellogg-Rust-Westinghouse)
  − IGT U-GAS /CI
Oxygen-steam gasifiers-2

Entrained Flow

• Dry-feed upflow
  – Koppers-Totzek (P = 1 atm)
  – Prenflo (prev. Krupp-Koppers)
  – Shell SCGP (Shell Coal Gasif’n Process)

• Slurry-feed
  – Texaco/GE CVX (down-flow)
  – DESTECH E-GAS (prev. Dow) 2-stage up-flow
  – Siemens (ex-Noell-GSP) (down-flow)