My Agenda

• CCS Economics
  - Economic methodology
  - Key economic indicators for CCS
  - Economics of CCS – current thinking

• Some closing thoughts
Economic methodology – a refresher...

• **Cash Flow**
  – Net CF = ‘cash in’ (revenue) - ‘cash out’ (project costs) over a defined time period
  – Incremental NCF
  – Why is CF useful?
    • Show changing costs over time
    • Show other factors (eg tax) over any part of lifetime
    • Show full lifetime economics

• **Value**
  – Future Value (FV), Present Value (PV)
  – Net Present Value (NPV)
  – Why is NPV useful?
    • Show project costs as a single number
    • Assess project viability (NPV > 0)
‘Cash in’ – Revenue opportunities for CCS

- Potential sales from Enhanced Oil Recovery (CO$_2$-EOR)
- Potential sales from Enhanced Coal Bed Methane (ECBM) production
- Potential sales for Enhanced Gas Recovery (CO$_2$-EGR)
- Potential sales for other applications (minerals, chemicals)
- Carbon credits (eg under ETS)
‘Cash out’ – Project costs for CCS

- Capital expenditure (‘CAPEX’)
- Operating expenditure (‘OPEX’)
- End-of-life (abandonment) expenditure (‘ABANDEX’ !)
- Taxes
CAPEX (one-off costs)

- Equipment
  - \( \text{CO}_2 \) capture plant
  - \( \text{CO}_2 \) purification plant
  - Storage tanks
  - By-product treatment
  - Compressors
  - Pipelines
  - Platforms
  - Well drilling
  - Monitoring equipment

- Installation & construction labour

- Escalation

- Owners’ costs - including:
  - Contingency
  - Permits & licensing
  - Site exploration & characterisation
  - Land acquisition/right of way
  - Project development
  - Environmental impact
  - Project financing
  - Currency risk
  - Taxes
  - Import duties
  - Warranties
  - Insurances
  - Start-up & commissioning
OPEX (on-going costs)

- Operating labour
- Maintenance labour
- Consumables
  - Water
  - Chemicals
  - Spare parts
- Fuel/energy requirements
- Externally supplied utilities
- Waste disposal
- Inspection services
- Insurances
- Special taxes (e.g., CO\textsubscript{2} emissions)
- Transport tariffs
- Major overhaul costs
- Monitoring
‘ABANDEX’ (end-of-life costs)

• Closing wells
• Dismantling and removing platforms
• Decommissioning, dismantling and removing process equipment
• Salvaging equipment (where possible)
• Site remediation and restoration
• On-going monitoring
Net Cash Flow - example

CBM project: CBM CAPEX $1B, CBM OPEX £100M/y, sales of CBM $350M/y

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>350</td>
<td>350</td>
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<td>CAPEX ($million)</td>
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</tr>
<tr>
<td>OPEX ($million)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
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<tr>
<td>Net CF ($million)</td>
<td>-500</td>
<td>-500</td>
<td>250</td>
<td>250</td>
<td>250</td>
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</tbody>
</table>
CCS project lifetimes

- ‘Build’ phase – 2-3 years
- ‘Operate’ phase – 20-40 years
- ‘Abandon’ phase – 1+ years
- Long-term liability/stewardship – 10-30 years after injection ceases?
### Incremental Net Cash Flow – example (1)

Similar project but with ECBM from outset: As before but additional CAPEX for CCS $500M, additional OPEX for CCS £80M/y, additional sales of CBM $70M/y

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<thead>
<tr>
<th>Year</th>
<th>1</th>
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<td>CAPEX ($million)</td>
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<td>OPEX ($million)</td>
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<td>100</td>
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<tr>
<td></td>
<td>Net CF ($million)</td>
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<tr>
<td></td>
<td>-750</td>
<td>-750</td>
<td>240</td>
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### Incremental Net Cash Flow – example (2)

Similar project but with ECBM from outset: As before but additional CAPEX for CCS $500M, additional OPEX for CCS £80M/y, additional sales of CBM $70M/y

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
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<td><strong>Revenue ($million)</strong></td>
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<td>350 +70</td>
<td>350 +70</td>
<td>350 +70</td>
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<tr>
<td><strong>CAPEX ($million)</strong></td>
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<td>500 +250</td>
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<td></td>
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<tr>
<td><strong>OPEX ($million)</strong></td>
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<td></td>
<td>100 +80</td>
<td>100 +80</td>
<td>100 +80</td>
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<tr>
<td><strong>Net CF ($million)</strong></td>
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<td>-750</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td><strong>Incr. NCF of CCS ($million)</strong></td>
<td>-250</td>
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<td>-10</td>
<td>-10</td>
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</table>
Future Value and Present Value

- What is the future value of $100 after 2 years at an interest rate of 10%?
  
  After 1 year: value = $100 \times (1+10\%) = $110  
  After 2 years: value = $100 \times (1+10\%) \times (1+10\%) = $121  
  After ‘n’ years: value = $100 \times (1+10\%)^n

- What is the present value of $100 in July 2013 at an interest rate of 10%?
  
  PV = $100 / (1+10\%)^2 = $82.6

- PV = FV / (1+d\%)^n

  Discount Factor = 1 / (1+d\%)^n
### PVs for ECBM example

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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</thead>
<tbody>
<tr>
<td>Discount Rate</td>
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<td>10%</td>
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<tr>
<td>Discount Factor</td>
<td>0.91</td>
<td>0.83</td>
<td>0.75</td>
<td>0.68</td>
<td>0.62</td>
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<tr>
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<td>240</td>
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<tr>
<td>PV ($million)</td>
<td>-683</td>
<td>-621</td>
<td>180</td>
<td>164</td>
<td>149</td>
</tr>
</tbody>
</table>
## NPV for ECBM example

### NPV = \bullet PV

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
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</thead>
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<tr>
<td>Discount Rate</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Discount Factor</td>
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<td>0.83</td>
<td>0.75</td>
<td>0.68</td>
<td>0.62</td>
</tr>
<tr>
<td>Net CF ($million)</td>
<td>-750</td>
<td>-750</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>PV ($million)</td>
<td>-683</td>
<td>-621</td>
<td>180</td>
<td>164</td>
<td>149</td>
</tr>
<tr>
<td>NPV ($million)</td>
<td>-683</td>
<td>-1304</td>
<td>-1124</td>
<td>-960</td>
<td>-811</td>
</tr>
</tbody>
</table>
Key economic indicators for CCS

BEWARE - TREAD CAREFULLY!

Three key indicators:

- Levelised cost of production (ie $/MWh, $/tonne, $/bbl, $/GJ)
- Cost of CO₂ avoided ($/tonne CO₂)
- Cost of CO₂ captured ($/tonne CO₂)
Levelised cost of production (LCOP)

• Standard metric for assessing project economics
• LCOP represents the revenue per unit of product that must be met to breakeven over the lifetime of the plant (ie zero profit)
• For CCS, this includes all costs incurred from capture, compression, transportation and long-term storage
• Best indicator for representing impact on consumers and society
• For power generation project – Levelised Cost of Electricity (LCOE)
• Economic assessment of a CCS project: Incremental increase in LCOP resulting from implementing CCS, eg:

\[ \text{LCOE} = \text{LCOE}_{\text{with CCS}} - \text{LCOE}_{\text{Ref}} \]
\[
\text{LCOE} = \left( \frac{F_{\text{CRFP}}C_{\text{Capital}} + F_{\text{FOM}}C_{\text{FOM}}}{F_{\text{Cap E Annual}}} \right) + F_{\text{VOM}}C_{\text{VOM}} + F_{\text{Fuel}}C_{\text{Fuel H Rate}}
\]

For detailed methodology see:
'Strategic Analysis of the Global Status of Carbon Capture and Storage, Report 2 (Economic Assessment of CCS Technologies)', Appendix A
Global CCS Institute, 2009
Cost of CO₂ avoided

• ‘CO₂ avoided’ is not the same as ‘CO₂ captured’ due to the energy penalty of CCS:

**Before CCS**

- 100tCO₂ generated by plant
- 100tCO₂ emitted

**After CCS**

- 100tCO₂ generated by original plant
- 30tCO₂ generated by CCS
- Capture and store 90% of total CO₂ generated
- 13tCO₂ emitted
- 87tCO₂ avoided
Cost of CO$_2$ avoided

- CO$_2$ avoided = CO$_2$ emitted without CCS minus CO$_2$ emitted with CCS
- More useful if expressed in terms of **emission intensity** (per unit of product – for power generation, tonnes/MWh): A$_{CO2\_Ref}$ and A$_{CO2\_Capt}$
  - measures overall effectiveness of a process in reducing CO$_2$ emissions
  - Can be considered as a measure of environmental impact
- Cost of CO$_2$ avoided:

\[
C_{CO2\_Avoided} = \frac{LCOE_{with\_CCS} - LCOE_{Ref}}{A_{CO2\_Ref} - A_{CO2\_Capt}}
\]
Cost of CO₂ captured

- Cost of CO₂ captured is cost of CCS required to capture, transport and place unit of CO₂ into storage.
- Useful for understanding value of CO₂ to end-use application, or actual cost of CCS to operator/system.
- Differs from LCOP in that CCS costs are normalised to the amount of CO₂ captured and stored instead of amount of product produced.

\[
C_{\text{CO₂ Captured}} = \frac{\text{LCOE}_{\text{with CCS}} - \text{LCOE}_{\text{Ref}}}{A_{\text{CO₂ Capt Gen}} - A_{\text{CO₂ Capt}}}
\]
**Significant factors**

<table>
<thead>
<tr>
<th>General Factors</th>
<th>Specific Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Location in world</td>
<td>• Capture specific:</td>
</tr>
<tr>
<td>• Technology factors:</td>
<td>– Technology choices</td>
</tr>
<tr>
<td>– ‘Brownfield’ vs ‘greenfield’</td>
<td>– Chemicals</td>
</tr>
<tr>
<td>– Technology maturity</td>
<td>– Fuel costs</td>
</tr>
<tr>
<td>• Labour factors:</td>
<td>• Transport specific:</td>
</tr>
<tr>
<td>– Rates</td>
<td>– Routes, booster pumps etc</td>
</tr>
<tr>
<td>– Unionised</td>
<td>– Flow through pipelines</td>
</tr>
<tr>
<td>• Commercial factors</td>
<td>• Storage specific:</td>
</tr>
<tr>
<td>– Risks</td>
<td>– ‘Finding costs’</td>
</tr>
<tr>
<td>– Contingencies</td>
<td>– Capacity</td>
</tr>
<tr>
<td>– Warranties and insurances</td>
<td>– Injectivity</td>
</tr>
<tr>
<td>– Price of $CO_2$</td>
<td>– Containment</td>
</tr>
</tbody>
</table>
Technology maturity: Demo, FOAK & NOAK

RD&D

- Demonstration plant
- Pilot plant
- Technology component/subsystem

Commercial Deployment

- First-of-a-kind (FOAK) commercial-scale plant
- 2nd-of-a-kind commercial plant
- nth-of-a-kind (NOAK) - fully mature

Capital Cost

Number of Plant in Operation

‘Capital Cost Learning Curve’
Technology maturity: TRLs and CCS

- How ‘ready’ are CCS technologies?

<table>
<thead>
<tr>
<th>Technology, System Test, Qualification and Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRL 9: Actual Technology system qualified through successful mission operations.</td>
</tr>
<tr>
<td>TRL 8: Actual Technology system completed and qualified through test and demonstration.</td>
</tr>
<tr>
<td>TRL 7: Technology system prototype demonstration in an operational environment.</td>
</tr>
<tr>
<td>TRL 6: Technology system / subsystem model or prototype demonstration in a relevant environment.</td>
</tr>
<tr>
<td>TRL 5: Technology component and / or basic technology subsystem validation in a relevant environment.</td>
</tr>
<tr>
<td>TRL 4: Technology component and / or basic technology subsystem validation in a laboratory environment.</td>
</tr>
<tr>
<td>TRL 3: Analytical and experimental critical function and / or characteristic proof-of-concept.</td>
</tr>
<tr>
<td>TRL 2: Technology concept and / or application formulated.</td>
</tr>
<tr>
<td>TRL 1: Basic principles observed and reported.</td>
</tr>
</tbody>
</table>

DG/Weyburn, Sleipner, In Salah, Snøhvit

20+ proposed demos in EU, NAM, Australia, etc

Many large pilot plants and smaller pilots

COMTES700, looping

Some ‘2nd generation’

Most ‘2nd generation’
Economics of CCS – current thinking

• Many and varied sources on CCS economics, BUT:
  • Much of the data available is outdated...
  • Much does not properly address risk or challenges...
  • Much does not address the whole CCS-chain...
  • Much does not have a transparent methodology...
  • Much does not provide for sensitivity analysis...
  • Try to use unbiased analysis from major, broad-based initiatives (eg IEA, CSLF, ZEP, IPCC, GCCSI)
  • Most recently conducted analysis for GCCSI (WorleyParsons, Schlumberger, Baker & McKenzie, EPRI) – 2011 update
## Economics of CCS – current thinking (2010$)

<table>
<thead>
<tr>
<th>Levelised Cost of Production</th>
<th>Power Generation</th>
<th>Industrial Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without CCS^2</td>
<td>PC (SC &amp; USC^1)</td>
<td>Oxy-comb (Std &amp; ITM^1)</td>
</tr>
<tr>
<td></td>
<td>73-76</td>
<td>73-76^3</td>
</tr>
<tr>
<td>With CCS (FOAK)^3</td>
<td>120-131</td>
<td>114-123</td>
</tr>
<tr>
<td>With CCS (NOAK)^4</td>
<td>117-129</td>
<td>112-121</td>
</tr>
<tr>
<td>% increase over w/o CCS^5</td>
<td>61-76%</td>
<td>53-65%</td>
</tr>
</tbody>
</table>

| Cost of CO₂ Avoided^6        | FOAK  | 62-81 | 47-59 | 67    | 107  | 54  | 54  | 19  | 20  |
|                              | NOAK  | 57-78 | 44-57 | 63    | 103  | 49  | 49  | 19  | 20  |

| Cost of CO₂ Captured^7        | FOAK  | 53-55 | 42-47 | 39    | 90   | 54  | 54  | 19  | 20  |
|                              | NOAK  | 52    | 41-45 | 38    | 87   | 49  | 49  | 19  | 20  |

Source – GCCSI (2011)
Notes for previous table

1. USC and ITM technologies currently under development - used to represent potential for increasing efficiency and reduced costs

2. Without CCS, the COP used for industrial processes are typical market prices for the commodities

3. Oxyfuel systems not typically configured to operate in air-fired mode (ie without CCS is not an option). PC without CCS used as reference for calculating cost of CO₂ avoided

4. For industrial processes, LCOP presented as increments above current costs

5. Percentage increase is expressed with respect to current commodity prices for industrial processes

6. Reference plant for cost of CO₂ avoided from coal-fired technologies is PC SC. Some previous studies selected reference plant as similar technology but without CCS
**Alstom cost study (2011): View out to 2030**

Cost increase <50% by 2030 for both Coal and Gas

Cost of CO2 avoided: 37 €/t for coal and 49 €/t for gas in 2030
Alstom cost study (2011): Fossil power with CCS costs no more than renewables

CoE - Low Carbon technologies Europe in 2011-2016 period

Cost of CCS Gas < Onshore Wind < CCS Coal
CCS < Offshore Wind and Solar

Reference case

Source: Alstom analysis 2011. CCS 2015 costs, including on shore T&S and CO₂ price (Flue Gas Recirculation case for CCS Gas CC, average Amine/Oxy for CCS Hardcoal)

CoE for CCS on Coal and Gas fired power competitive even without including the system costs of intermittent generation
Closing Thoughts... CCS Economics (1)

• ‘CCS community’ needs broad understanding of CCS economics, including key methodologies for project economics.

• Key CCS economic indicators give different perspectives: LCOP (anticipated cost increase to end product, impact on consumers or society), $C_{CO2}$ avoided (value of CO$_2$, actual cost of CCS to operator/system), $C_{CO2}$ Captured (costs to the process). Care needed!

• CCS in power generation and many industrial processes increases CAPEX, OPEX and ABANDEX, creating an economic hurdle. Generally, CCS costs exceed potential revenue streams.

• CCS project lifetimes are long - uncertainty on long-term liability issue.

• Good economic data for CCS is available - choose sources carefully and read caveats/footnotes. Differences generally due to assumptions (technology performance, input costs, ‘levelisation’ methodology).

• Technical maturity: CCS generally still in RD&D phase. Demo and FOAK costs high compared to NOAK. Cost reduction potential in ‘1$^{st}$ generation’ (3-5%). Major reductions anticipated for 2$^{nd}$/3$^{rd}$ generation.
Closing Thoughts... CCS Economics (2)

• Project costs can vary considerably – remember the ‘factors’ (location, technology, labour, commercial, capture/transport/storage specifics).

• Largest uncertainty in costs is up-front CAPEX. Adding CCS adds between ~30% (pre-comb) and 80-100% (post/oxy-comb) to CAPEX.

• Currently difficult to pick single capture technology with clear cost advantage: Oxy-comb looking good (LCOP, C_{CO2 avoided}) but least mature.

• Storage costs very dependent on geology (but generally contribute <5% of total in ideal sites or up to ~10% in poorer sites).

• More design studies → better understanding of costs. So far, many more completed on IGCC+pre-comb (and costs have drifted up...).

• Studies in 2010 show cost estimates consistently higher than 2-3 years ago (inclusions, changing methodologies, etc). Costs now suggested to be ~15-30% higher than earlier estimates (GCCSI).