Future-proofing coal plants with post-combustion capture against technology developments

Mathieu Lucquiaud (a), Xi Liang (b), Olivia Errey (a), Hannah Chalmers (a), Jon Gibbins (a)

m.lucquiaud@ed.ac.uk

(a) University of Edinburgh, (b) University of Exeter,
Future-proofing capture plants against technology developments

- Capture technology is going to change
A MODEL FOR CCS DEPLOYMENT

RETROFIT 1st UNITS WITH 2nd GENERATION SOLVENTS

FIRST TRANCHE
Demonstration

SECOND TRANCHE
Commercial & Regulatory Drivers

LEAD COUNTRY CCS ROLLOUT
Big prize is getting two learning cycles from two tranches of CCS projects before global rollout

TODAY

1st generation solvents

1st and 2nd generation solvents

2nd generation solvents and beyond
Future-proofing capture plants against technology developments

- Capture technology is going to change

- Motivations for future-proofing power generation asset
  - Keep the plant license to operate by securing compliance with stricter environmental legislation
  - New solvent becomes Best Available Technology (e.g. for lower carryover in flue gas)
  - Level of capture has to be increased beyond ~ 90%
Future-proofing capture plants against technology developments

- **Capture technology is going to change**

- **Motivations for future-proofing power generation asset**
  - Keep the plant license to operate by securing compliance with stricter environmental legislation
  - New solvent becomes Best Available Technology (e.g. for lower carryover in flue gas)
  - Level of capture has to be increased beyond ~ 90%

- **Improve power plant economics**
  - Increase plant capacity (MW sent out for sale)
  - Raise efficiency
  - Reduce exposure to carbon costs
  - Reduce operating costs
  - Enhance reliability and availability
Methodology – Step 1

- What is a better solvent?
  - Focus on electricity output penalty and overall process assessment
    
    Electricity output penalty = 
    
    \[
    \frac{\text{loss of generator output} + \text{compression power} + \text{ancillary power}}{\text{CO2 mass flow}}
    \]

- Dedicated steam cycle and compression model
  
  Relate electricity output penalty of new-build plants to key amine process parameters
    
    - Solvent energy of regeneration, GJ/tCO2
    - Solvent temperature of regeneration, ºC
    - Desorber and delivery pressure, bar
    - Ancillary power, kWh/tCO2

Illustration of trade-offs between key amine process parameters

Reference line: EOP of 290 kWh/tCO2, desorber pressure of 2 bar, solvent energy of regeneration of 3.2 GJ/tCO2 and ancillary power for the amine plant of 20 kWh/tCO2.
Methodology – Step 2

- **Sensitivity of electricity output penalty to key solvent parameters**
  - Specific heat capacity
  - Thermal stability
  - Enthalpy of absorption
  - Mass transfer

- **Reference plant:** New-build unit with post-combustion capture
  Reference solvent: 30%wt MEA

- **Objectives of methodology:**
  - Generate a range of hypothetical solvents, i.e. normally related key solvent parameters are now artificially independent
  - Assess performance for dedicated new-build plants for each solvent
  - Identify pieces of equipment leading to performance lock-in
Rate-base absorber model within a generic amine flowsheet

- From boiler
- Ancillary power
- Reboiler temperature
- Energy of regeneration
- Into dedicated compression and power plant model
- Desorber pressure
- to stack
Future-proofing coal plants
Sensitivity of performance to solvent heat capacity

Preliminary results

Electricity output penalty (kWh/tCO₂)

solvent lean loading (mol/mol)

+30%
+15%
reference
-15%
-30%
Future-proofing coal plants
Sensitivity of performance to solvent thermal stability

Preliminary results

Graph showing the relationship between solvent reboiler temperature (°C) and GJ/tCO₂ for thermal energy of regeneration and desorber pressure.
Sensitivity of performance to solvent thermal stability
Example of performance lock-in

Preliminary results

Area of performance lock-in with a non-upgradeable steam turbine systems

Overall EOP
EOP steam extraction
EOP compression
Critical pieces of equipment and related solvent properties

- Steam turbine – solvent temperature and energy of regeneration
- Absorber – kinetics and mass transfer
- Compression - enthalpy of absorption, solvent temperature of regeneration
- Desorber - enthalpy of absorption, solvent temperature of regeneration
- Pipeline (if increased capture levels)
Economic assessment of upgrading CCS plants

Two key research questions:

- What is the financial value of the option of being able to upgrade a pulverised coal-fired power plant with CO2 capture with a new solvent/process?
- What are the potential strategies to inform the investment decision concerning the upgrade of the plant, i.e. whether and when to exercise a possible upgradability option?
Methodology – Step 3

- Methodology Summary:
  - Real option approach with a stochastic cash flow model.
  - Long run marginal costs are used to justify the upgrade decision.
Methodology – Step 3

Methodology Summary:

- Real option approach with a stochastic cash flow model.
- Long run marginal costs are used to justify the upgrade decision.
- Technology progress ratio is 92%, i.e. a reduction of 8% of the electricity output penalty occurs per doubling of the global installed capacity of post-combustion capture plant.
- The deployment rate follows the IEA Blue Map Scenario.
<table>
<thead>
<tr>
<th>Parameters (USD)</th>
<th>Input</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Life</td>
<td>25 years</td>
<td>From Operation</td>
</tr>
<tr>
<td>Risk-free Rate</td>
<td>2%</td>
<td>real</td>
</tr>
<tr>
<td>Base Year</td>
<td>2004 Price Level</td>
<td></td>
</tr>
<tr>
<td>Gross Output (MW)</td>
<td>827MW</td>
<td>IEA GHG PH4/33 Study (Net Output 666MW)</td>
</tr>
<tr>
<td>Fixed Capital (Capex)</td>
<td>1249 million</td>
<td>at year 0</td>
</tr>
<tr>
<td>Working Capital</td>
<td>9 million</td>
<td>IEA GHG PH4/33 Study</td>
</tr>
<tr>
<td>Upfront Capex for Upgrade</td>
<td>5% of Original</td>
<td>Sensitivity analysis with ±1% and ±2% Fixed Capital</td>
</tr>
<tr>
<td>EOP without Upgrade</td>
<td>257 kWh/tonne</td>
<td></td>
</tr>
<tr>
<td>Net Supply Efficiency (LHV)</td>
<td>44%</td>
<td>At full load (degrading by 1.5%)</td>
</tr>
<tr>
<td>Load Factor</td>
<td>85%</td>
<td>For 2-25 years; year 1: 60%</td>
</tr>
<tr>
<td>Coal Price</td>
<td>4 $/GJ with 2% real growth</td>
<td>10% std dev</td>
</tr>
<tr>
<td>CO₂ Emissions Cost</td>
<td>start 25 euro/t with a real</td>
<td>4% and 20% std dev</td>
</tr>
<tr>
<td></td>
<td>growth of 4% and 20% std dev</td>
<td></td>
</tr>
<tr>
<td>Emissions Factor Baseline</td>
<td>743 gram/kWh</td>
<td></td>
</tr>
<tr>
<td>Emissions Factor with CO₂ Capture</td>
<td>117 gram/kWh</td>
<td></td>
</tr>
<tr>
<td>Coal Feed Rate</td>
<td>0.00817 GJ/kWh</td>
<td></td>
</tr>
<tr>
<td>Fixed O&amp;M</td>
<td>85 million/year</td>
<td></td>
</tr>
<tr>
<td>Fixed O&amp;M after Upgrade</td>
<td>unchanged</td>
<td></td>
</tr>
<tr>
<td>Learning Rate of EOP</td>
<td>0.92</td>
<td>with sensitivity analysis</td>
</tr>
<tr>
<td>Financing Cash Flow</td>
<td>not considered</td>
<td></td>
</tr>
</tbody>
</table>
Methodology – Step 3

Methodology Summary:

- Real option approach with a stochastic cash flow model.
- Long run marginal costs are used to justify the upgrade decision.

- Technology progress ratio is 92%, i.e. a reduction of 8% of the electricity output penalty occurs per doubling of the global installed capacity of post-combustion capture plant.
- The deployment rate follows the IEA Blue Map Scenario.

- Least square regression with Monte-Carlo simulation is used to model the financial value at each option decision node.
- Uncertainties on coal price, carbon price and technology improvement rates are the drivers for the options value.
- The main driver for the upgrade is a possible reduction of the electricity output penalty as new technologies enter the market.
Value of the upgradability option: 92% progress ratio

<table>
<thead>
<tr>
<th>(Million:US$)</th>
<th>Option Value (Only One Upgrade Option)</th>
<th>Option Value (Multiple Options)</th>
<th>Δ COE with Multiple Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>117.5</td>
<td>126.7</td>
<td>-1.92</td>
</tr>
<tr>
<td>Std Dev</td>
<td>32.1</td>
<td>33.2</td>
<td>0.45</td>
</tr>
<tr>
<td>Std Err</td>
<td>0.3345</td>
<td>0.3672</td>
<td>0.002844</td>
</tr>
<tr>
<td>Max</td>
<td>249.4</td>
<td>279.3</td>
<td>-0.52</td>
</tr>
<tr>
<td>Min</td>
<td>19.2</td>
<td>19.5</td>
<td>-2.79</td>
</tr>
</tbody>
</table>
## Sensitivity analysis

### 1. Change in Progress Ratio

<table>
<thead>
<tr>
<th>Progress Ratio</th>
<th>Option Value (US$ million)</th>
<th>Impact on COE (US$/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90%</td>
<td>165.3</td>
<td>-2.4</td>
</tr>
<tr>
<td>91%</td>
<td>145.4</td>
<td>-2.16</td>
</tr>
<tr>
<td>92%</td>
<td>126.7</td>
<td>-1.92</td>
</tr>
<tr>
<td>93%</td>
<td>104.3</td>
<td>-1.71</td>
</tr>
<tr>
<td>94%</td>
<td>85.5</td>
<td>-1.53</td>
</tr>
</tbody>
</table>

### 2. Change in the upfront additional CAPEX

<table>
<thead>
<tr>
<th>CAPEX (%)</th>
<th>Multiple Options (US$)</th>
<th>Impact on COE (US$/MWh)</th>
<th>Chance of Second Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>167.4</td>
<td>-2.04</td>
<td>99.92%</td>
</tr>
<tr>
<td>4%</td>
<td>148.5</td>
<td>-1.99</td>
<td>98.45%</td>
</tr>
<tr>
<td>5%</td>
<td>126.7</td>
<td>-1.92</td>
<td>79.32%</td>
</tr>
<tr>
<td>6%</td>
<td>108.9</td>
<td>-1.83</td>
<td>36.58%</td>
</tr>
<tr>
<td>7%</td>
<td>94.3</td>
<td>-1.76</td>
<td>12.01%</td>
</tr>
</tbody>
</table>
Conclusion

- Technology upgrade may be driven by future policies or technology developments.
- Future-proofing options need to include the overall CCS process, including the power plant and not only the amine plant in isolation.
- Future technology developments are by nature uncertain and potential savings are uncertain too:
  - Energy savings, timing for upgrade, Fuel and carbon cost, Capital cost
- Only low-cost options with high return can be justified.
  - Similar approach to implementation of capture-readiness on new-build plants without CCS.
- Limited additional upfront capital costs to future-proof CCS plants may be justified. The financial value of an future-proofing option is, however, strongly dependent on technology learning rate assumed.
- A first upgrade is very likely to take plant 7 to 10 years after the plant has been commissioned.
- A second upgrade during the plant lifetime is also very likely.
Forthcoming report commissioned by IEAGHG
Incorporating future technological improvements in existing CO$_2$ capture plants

Acknowledgments

- Funding from the UK Technology Strategy Board through the CASS-CAP project
- Funding from IEAGHG. Project managers Mohammad Abu-Zahra (until April 2011) and Mike Haines.