Evaluation of emissions of substances other than CO₂ from power plants with Post Combustion Capture

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IEAGHG
Content

» Impact of PCC on emissions. Importance and challenges.

» Methodology: two ways approach Harmonization and Modelling

» Model construction

» Cases: USC and NGCC

» Sensitivity analysis

» Conclusions and future work
Evaluation of emissions. Importance & challenges

- Uncertainties in the impact of CCS to the environment
- Scarcity in environmental data in relation to CCS
- Standardization and reliability in the existing data
- Broader study: among the technologies analyzed the focus here is on Post Combustion Capture (PCC)

Goal:
- Development of systematic and clear methodology for waste and emissions evaluation
- Quantify the effects of PCC technology on emissions of other substances than CO₂
Two way approach for evaluation of emissions

- **Harmonization**: statistical analysis of the emissions database created by reviewing the open literature. Corrections are applied to bring into line all cases in the database.
- **Modelling**: Commercial software package (Aspen Plus®) used to evaluate plant performance and basic emissions. Emission factors used for trace components.

Two different methods are used and compared.
### Evaluation framework (1)

<table>
<thead>
<tr>
<th>Case</th>
<th>1A</th>
<th>1B</th>
<th>4A</th>
<th>4B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>USC</td>
<td>USC</td>
<td>NGCC</td>
<td>NGCC</td>
</tr>
<tr>
<td>Steam Cycle bar(a)/ºC/ºC</td>
<td>290 / 600 / 620</td>
<td>290 / 600 / 620</td>
<td>124/561/234</td>
<td>124 /561/234</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>NA</td>
<td>NA</td>
<td>Advanced F class</td>
<td>Advanced F class</td>
</tr>
<tr>
<td>Boiler type</td>
<td>Supercritical PC</td>
<td>Supercritical PC</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>NOx Controls</td>
<td>Low NOx Burners &amp; OFA &amp; SCR</td>
<td>Low NOx Burners &amp; SCR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM Controls</td>
<td>ESP</td>
<td>ESP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H2S controls</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>SOx /Sulphur control</td>
<td>FGD (Wet Scrubber, Limestone)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CO2 separation</td>
<td>NA</td>
<td>MEA</td>
<td>NA</td>
<td>MEA</td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Australian Bituminous coal</td>
<td>Gas</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Case 1A: USC PC without PCC
Case 1B: USC PC with PCC
Case 4A: NGCC without PCC
Case 4B: NGCC with PCC

USC ultra supercritical
NGCC Natural Gas Combined Cycle
OFA: Overfire Air
SCR: Selective Catalytic Reduction

EBTF. European Benchmarking Task Force. Common framework definition document and Test cases 2010
### Evaluation framework (2)

<table>
<thead>
<tr>
<th>Technical criteria</th>
<th>Units</th>
<th>Technical criteria</th>
<th>Range found in emissions database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal type</td>
<td>[-]</td>
<td>Bituminous Eastern Australia</td>
<td>Different coal types</td>
</tr>
<tr>
<td>Sulphur content in coal</td>
<td>%wt dry</td>
<td>0.95</td>
<td>0.95 – 1.5</td>
</tr>
<tr>
<td>CO₂ Capture Removal</td>
<td>[%]</td>
<td>90%</td>
<td>80% - 100%</td>
</tr>
<tr>
<td>CO₂ product conditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>ºC</td>
<td>&lt;30</td>
<td>25 - 30</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar</td>
<td>110</td>
<td>80 - &gt; 156</td>
</tr>
</tbody>
</table>

- Standard MEA capture process was used as reference for capture
- Emissions generated from solvent degradation are excluded from this study
Harmonization: Treatment of the database

1. LITERATURE REVIEW
   - Emissions database
   - Open literature

2. HARMONIZATION
   - Reference cases
   - Technical criteria
   - Correction factors
     - Fuel use
     - Capture efficiency
     - Coal sulphur content

3. EVALUATION OF EMISSIONS
   - Harmonized Emissions database
   - Relative emissions factors

Data Sources (37)
- Existing operating power plants
- Case studies, peer reviewed journals
- Database (176 cases)

Harmonization: Application of correction factors that bring into line the basis of each case
Harmonization procedure

- Corrections were applied to:
  - Fuel use: Corrected for capture efficiency and CO₂ compression pressure
  - Capture efficiency for CO₂ emissions
  - Sulfur content in the coal for SOx emissions
Modelling: Process simulation and emission factors

STEP 1 - Process modelling Tools and Engineering calculations

Power Plant (Boiler island, steam turbine island and emission controls)

Fuel flow and composition
Air flow
Ammonia
Limestone

Flue gas after FGD:
Basic components:
CO2
N2
O2
H2O

Bottom ash / Fly ash
Unburned coal
Effluent
Gypsum

SO2, SO3
NO, NO2
PM, PM-10
Trace metals in Flue gas:
As, Hg, Se, Be, Pb, etc

Calculation of solvent loss due to:
Oxidation
Polymerisation
Reaction with acid gases

Caustic consumption in reclaimer
Activated carbon requirement

Solvent make-up

CO2 Depleted flue gas:
CO2, N2, O2, H2O

STEP 2 - Estimation of emission factors based on the given technology

CO2 capture and compression

SO2, SO3
NO, NO2
PM, PM-10
Trace metals in Flue gas:
As, Hg, Se, Be, Pb, etc

Liquid waste
Heat stable salts:
Na2SO4, Na3PO4
Effluent

Solid waste
Activated carbon impurities
Bottom ash / Fly ash
Unburned coal
Gypsum

CO2 Product
CO2
H2O
SO2
NOx

Waste inventory

Flue gas out:
CO2
N2
O2
H2O
SO2, SO3
NO, NO2
PM, PM-10
Trace metals:
As, Hg, Se, Be, Pb, etc

Cooling Water consumption
Electricity consumption (ID fan and pumps)

Energy required for solvent regeneration

Cooling Water output
Electricity output
Steam Output

Process Input

Technical Description
Interaction of flue gas impurities with solvent

1. Fix specific degradation rate due to oxidation
2. Concentration of salts in the inlet stream: 1% wt.
3. Fraction of the lean stream reclaimed: fixed to match the HSS formation rate
4. Bottoms: slurry containing 40% wt. water
5. Concentration of free amine in the system: 60 mol MEA / mol HSS
6. Concentration of free amine at the bottoms: 0.6 - 1 mol MEA/mol HSS

1. Degradation 0.23 - 0.73 kg/tonCO₂ @ 5%O₂
6. MPR Services Inc.
USC PC case

[Diagram of USC PC case with labeled components and flow paths]

- Cooling water supply
- Process water
- Limestone
- Steam turbine Island
- Unit 100 Coal handling
- Unit 200 Boiler Island
- ESP Removal Particulate matter
- Unit 400 DeNOx plant
- FGD and Handling plant
- CO2 removal
- Compression

Flow paths and labels indicate various processes and materials:
- Coal handling
- Boiling Island
- FGD and Handling plant
- CO2 removal
- Compression

Emission factors & removal efficiencies applied for these units as a block

Stream numbers inline with the reference study [5]
NGCC case

1. Gas
2. Air
3. Cooling water make up
4. Process water
5. Scrubber water
6. Heat recovery steam generator
7. Steam turbine
8. CO2 removal
9. CO2 compression & drying
10. CO2
11. Scrubber water
12. Flue gas to stack
13. Reclaimer waste
14. Scrubber water
15. Flue gas to stack
16. Waste water-1
17. Cooling water supply
18. Cooling water system
19. Waste water-2
20. Solvent make-up
21. Caustic

Emission factors & removal efficiencies applied for these units as a block.
Output from Harmonization

The Harmonization model was implemented in excel. Results include:

Fuel usage

Average emissions (CO2, SOx, NOx, PM-10, Ammonia) and standard deviation

Different capture technologies (focus on PCC)
Overall waste assessment
## Basic Performance of Power plants

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>1A</th>
<th>1B</th>
<th>4A</th>
<th>4B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal or Gas Flow rate (air dry)</td>
<td>t/h</td>
<td>239.8</td>
<td>266.3</td>
<td>56.1</td>
<td>56.1</td>
</tr>
<tr>
<td>Fuel LHV</td>
<td>kJ/kg</td>
<td>25870</td>
<td>25870</td>
<td>46502</td>
<td>46502</td>
</tr>
<tr>
<td>Gross Electricity Output (D)</td>
<td>MW~e</td>
<td>831</td>
<td>827</td>
<td>430.3</td>
<td>430.3</td>
</tr>
<tr>
<td>Power plant Auxiliaries (E)</td>
<td>MW~e</td>
<td>73.3</td>
<td>78.3</td>
<td>7.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Capture plant additional consumption (F)</td>
<td>MW~e</td>
<td>83.1</td>
<td></td>
<td></td>
<td>66</td>
</tr>
<tr>
<td>Net Electric Output (C = D - E - F)</td>
<td>MW~e</td>
<td>757.7</td>
<td>665.6</td>
<td>422.6</td>
<td>356.6</td>
</tr>
<tr>
<td>Net electrical efficiency (C/A*100)</td>
<td>% [LHV]</td>
<td>44.0</td>
<td>34.8</td>
<td>58.3</td>
<td>49.2</td>
</tr>
<tr>
<td>Specific fuel consumption</td>
<td>MW<del>t/ MW</del>e</td>
<td>2.07</td>
<td>2.88</td>
<td>1.71</td>
<td>2.03</td>
</tr>
<tr>
<td>Specific CO2 emissions</td>
<td>kg/MWh</td>
<td>743</td>
<td>117</td>
<td>354</td>
<td>41.9</td>
</tr>
<tr>
<td>Cooling water consumption</td>
<td>t/MWh</td>
<td>138.6</td>
<td>240.5</td>
<td>45.6</td>
<td>82.7</td>
</tr>
</tbody>
</table>

Cases 1A and 1B USC PC without and with PCC
Cases 4A and 4B NGCC cases without and with PCC
# Main gaseous emissions

<table>
<thead>
<tr>
<th>Basic components</th>
<th>Units</th>
<th>Modelling</th>
<th></th>
<th></th>
<th>Database</th>
<th></th>
<th></th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1A</td>
<td>1B</td>
<td>1A</td>
<td>1B</td>
<td>4A</td>
<td>4B</td>
<td>4A</td>
</tr>
<tr>
<td>CO₂</td>
<td>kg/MWhₙₑₜ</td>
<td>739</td>
<td>93</td>
<td>735</td>
<td>97</td>
<td>354</td>
<td>42</td>
<td>366</td>
</tr>
<tr>
<td>SO₂</td>
<td>kg/MWhₙₑₜ</td>
<td>0.26</td>
<td>6.5E-04</td>
<td>0.30</td>
<td>0</td>
<td>1,0E-02</td>
<td>5,9E-05</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>kg/MWhₙₑₜ</td>
<td>0.08</td>
<td>0.104</td>
<td>0.36</td>
<td>0.50</td>
<td>0,03</td>
<td>0,03</td>
<td>0.12</td>
</tr>
<tr>
<td>Acid gases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>kg/MWhₙₑₜ</td>
<td>0.07</td>
<td>0.09</td>
<td>NA</td>
<td>NA</td>
<td>0,09</td>
<td>0,10</td>
<td></td>
</tr>
<tr>
<td>HCl</td>
<td>kg/MWhₙₑₜ</td>
<td>0.009</td>
<td>5.4E-04</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HF</td>
<td>kg/MWhₙₑₜ</td>
<td>0.001</td>
<td>6.8E-05</td>
<td>NA</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particulates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM-10</td>
<td>kg/MWhₙₑₜ</td>
<td>0.01</td>
<td>0.006</td>
<td>0.04</td>
<td>0.062</td>
<td>9,7E-05</td>
<td>5,7E-05</td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
<td>kg/MWhₙₑₜ</td>
<td>0.107</td>
<td>0.004</td>
<td>0.08</td>
<td>0</td>
<td>0,04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SOₓ emissions estimated from the modelling study and harmonization study are in good agreement.

NOₓ emissions estimated from the modelling study are much lower than the estimates from the harmonization study.

PM shows a different trend between modelling and harmonization.
Main gaseous emissions. Analysis

- LNB & OFA & SCR combination available but not widely demonstrated
- Removal efficiency vary in operation from 85% to 95%
- Emission target for the present project was 100 mg/Nm³
- These controls are capable to reduce the levels to 13ppmv
# Trace components in gaseous emissions

## Classification of metals

1. **Class 1:** Little particle enrichment (manganese, beryllium, cobalt, and chromium).
2. **Class 2:** Enriched in fly ash relative to bottom ash (arsenic, cadmium, lead, and antimony).
3. **Class 3:** Emitted in the gas phase (primarily mercury and, in some cases, selenium).

## Trace Metals

<table>
<thead>
<tr>
<th>Trace metals</th>
<th>Units</th>
<th>1A</th>
<th>1B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>5.20E-05</td>
<td>5.20E-05</td>
</tr>
<tr>
<td>Cadmium</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>1.70E-06</td>
<td>1.70E-06</td>
</tr>
<tr>
<td>Chromium</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>4.00E-07</td>
<td>4.00E-07</td>
</tr>
<tr>
<td>Cobalt</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>1.20E-07</td>
<td>1.20E-07</td>
</tr>
<tr>
<td>Lead</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>5.20E-06</td>
<td>5.20E-06</td>
</tr>
<tr>
<td>Manganese</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>4.00E-07</td>
<td>4.00E-07</td>
</tr>
<tr>
<td>Nickel</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>6.40E-05</td>
<td>8.10E-05</td>
</tr>
<tr>
<td>Selenium</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>5.30E-04</td>
<td>6.70E-04</td>
</tr>
<tr>
<td>Zn</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>1.50E-02</td>
<td>1.90E-02</td>
</tr>
<tr>
<td>Copper</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>1.10E-04</td>
<td>1.40E-04</td>
</tr>
<tr>
<td>Total mercury</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>5.70E-06</td>
<td>5.30E-06</td>
</tr>
<tr>
<td>Hg&lt;sup&gt;0&lt;/sup&gt;</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>4.20E-06</td>
<td>4.90E-06</td>
</tr>
<tr>
<td>Hg&lt;sup&gt;2+&lt;/sup&gt;</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>1.50E-06</td>
<td>4.50E-07</td>
</tr>
<tr>
<td>Hg&lt;sup&gt;p&lt;/sup&gt;</td>
<td>kg/MWh&lt;sub&gt;net&lt;/sub&gt;</td>
<td>4.00E-08</td>
<td>2.60E-08</td>
</tr>
</tbody>
</table>

---

1. AP-42 ((accesed 2009)). "Compilation of Air Pollutant Emission factors." US Environmental protection Agency
## Generated waste. Liquid and solid emissions

<table>
<thead>
<tr>
<th>Generated waste</th>
<th>Units</th>
<th>1A</th>
<th>1B</th>
<th>4A</th>
<th>4B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles in ESP</td>
<td>kg/MWh_{net}</td>
<td>19</td>
<td>24</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Gypsum</td>
<td>kg/MWh_{net}</td>
<td>15</td>
<td>21</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Furnace bottom ash</td>
<td>kg/MWh_{net}</td>
<td>9.6</td>
<td>12</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Fly ash</td>
<td>kg/MWh_{net}</td>
<td>29.0</td>
<td>37</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Mill rejects</td>
<td>kg/MWh_{net}</td>
<td>0.7</td>
<td>0.8</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Reclaimer waste</td>
<td>kg/MWh_{net}</td>
<td>NA</td>
<td>3.291</td>
<td>NA</td>
<td>1.17</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>kg/MWh_{net}</td>
<td>NA</td>
<td>0.063</td>
<td>NA</td>
<td>0.025</td>
</tr>
</tbody>
</table>

### Raw Materials

<table>
<thead>
<tr>
<th>Raw Materials</th>
<th>Units</th>
<th>1A</th>
<th>1B</th>
<th>4A</th>
<th>4B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling water consumption</td>
<td>t/MW h</td>
<td>138.6</td>
<td>240.5</td>
<td>45.6</td>
<td>82.7</td>
</tr>
<tr>
<td>Specific water consumption</td>
<td>t/MW h</td>
<td>0.104</td>
<td>0.410</td>
<td>1.01</td>
<td>1.21</td>
</tr>
<tr>
<td>MEA make up</td>
<td>kg/tonCO\textsubscript{2}</td>
<td>1.765</td>
<td>1.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activated carbon make up</td>
<td>kg/tonCO\textsubscript{2}</td>
<td>0.075</td>
<td>0.075</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sensitivity analysis. MEA degradation at higher oxygen concentrations

\[-r_{\text{MEA}} = k_0 e^{\left(\frac{45300}{RT}\right)} \cdot [\text{MEA}]^{0.91} \cdot [\text{CO}_2]^{-0.33} \cdot \left([\text{SO}_2]^{0.42} + [\text{O}_2]^{0.78}\right)\]

Sensitivity analysis.
Waste generation at higher sulphur content

CASE 1B Emissions of SOx for different desulphurisation efficiencies

CASE 1B Generated flows with an desulphurisation efficiency of 95% & 98%
Conclusions and future work

- Overall waste assessment of PCC applied to two different power plants has been performed by different methods:
  - Harmonization: useful tool for estimating relative emissions in those cases where technology is well established and much information regarding emissions is reported.
  - Modelling: possibility to cover the uncertainties on the emissions of novel technology.
- Uncertainties on degradation rates, rates of HSS formation need to be further investigated.
- USC PC has higher emissions of pollutants than NGCC. However, the higher oxygen concentration in the NGCC case might lead to more generated waste in the reclaimer.
- Possibilities of waste reduction need to be further investigated.
Extra slides (1)

Composition of CO₂ stream (Case 1B)

- CO₂ >99.9%
- SO₂ 34ppmw
- SO₃ <21ppmw
- NO₂ <7ppmw
- HCl <2ppmw
- Hg²⁺ <2ppbw

Assumption is that 75% of the sulphur capture in the CO₂ unit is recovered as HSS